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STUDIES OF THE ARMY AVIATION (V/STOL) ENVIRONMENT. REPORT NUMBER 5. OCCURRENCE OF ICE IN THE FORM OF GLAZE, RIME, AND HOARFROST WITH RESPECT TO THE OPERATION AND STORAGE OF V/STOL AIRCRAFT

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13. ABSTRACT

As part of a series entitled "Studies of the Army Aviation (V/STOL) Environment," this report describes the nature and worldwide occurrence of ice in the form of glaze, rime, and hoarfrost from the surface to 20,000 feet in accordance with contract requirements. Because of the nature of available sources and scarcity of data for these phenomena in most parts of the world, this study is more descriptive than quantitative.

It was found that glaze, rime, and hoarfrost form within a very specific and rather narrow range of meteorological conditions where air and affected surface temperatures are slightly above, at, or below 0° C (32° F) and moisture, usually supercooled, is present. Icing may thus be produced at ground level by glaze storms, fog, humid air, or thaw-freeze action, and in the atmosphere by clouds or moist air. Geographic distribution of these icing phenomena is dependent on a variety of physical factors.

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SUMMARY

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U. S. ARMY ENGINEER TOPOGRAPHIC LABORATORIES
FORT BELVOIR, VIRGINIA

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OCCURRENCE OF ICE IN THE FORM OF GLAZE, RIME, AND HOARFROST WITH RESPECT TO THE OPERATION AND STORAGE OF V/STOL AIRCRAFT

(Report No. 5 of "Studies of the Army Aviation (V/STOL) Environment")

January 1973

Distributed by

The Commanding Officer
U. S. Army Engineer Topographic Laboratories

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FOREWORD

This report is another in a series of studies conducted by the Geographic Sciences Laboratory, U. S. Army Engineer Topographic Laboratories, to provide information on elements of the natural environment having operational significance to Army Aviation (V/STOL) aircraft during times of hover, landing, and takeoff. The information presented will guide the requesting agency, the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, in determining the criteria to be adopted as environmental standards in the design and testing of Army Aviation (V/STOL) aircraft systems.

This report presents information on the nature and occurrence of icing in the form of glaze, rime, and hoarfrost under the limitations of available sources and contract requirements. It is identified as Report No. 5 of the series "Studies of the Army Aviation (V/STOL) Environment," and was produced under Project Task 1F162203A11906 of the Reliability and Maintainability Division, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia.

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OCCURRENCE OF ICE IN THE FORM OF GLAZE, RIME, AND HOARFROST WITH RESPECT TO THE OPERATION AND STORAGE OF V/STOL AIRCRAFT

I. INTRODUCTION

The hazards of aircraft icing have special implications for rotary-wing V/STOL aircraft. The following statements from the 5th Weather Wing Forecaster's Seminar No. 36 on Weather and Helicopter Operation from the Department of the Air Force indicate the significance of icing to rotary-wing aircraft operation:

> Due to the relatively high speed of the rotor, ice accumulates at a rapid rate on the leading edges of the blades, the point of maximum lift, thereby destroying total lift in a very short length of time. . . . But the first and most dangerous icing will occur in the rotor head. . . . If allowed to build up [there] for even a few minutes, it will prohibit control movement, and the helicopter will become uncontrollable. . . . Frost on the rotor blades will probably prohibit takeoff. . . . If a takeoff should be possible with frost on the blades, the frost may exaggerate the loss of lift when leaving the ground cushion and cause an unintentional touchdown. . . . Takeoff from a frozen surface also poses a unique problem. If the tires are frozen to the surface and are not freed prior to attempting takeoff, they may break loose unsymmetrically and cause the helicopter to tilt. . . . [and] tipping may cause them [the blades] to strike the surface. . . .

It is generally acknowledged that icing at the surface and in the atmosphere takes three basic forms distinguishable by appearance and genesis. Terminology for the three forms does not seem to be universally standardized, but "glaze," "rime," and "hoarfrost" are commonly used when distinctive categories for icing are needed. All three describe a coating of ice on a cold surface exposed somehow to the atmosphere under weather conditions providing moisture and temperatures slightly above, at, or below 0° C (32° F). As observed, such a coating of ice prohibits the in-flight operation of V/STOL aircraft and temporarily immobilizes field-stored V/STOL aircraft. Information concerning the geographic distribution, frequency of occurrence, probability of occurrence, and thickness of such ice is needed to determine regions of hazardous operation for design and qualification requirement considerations.

II. THE NATURE AND OCCURRENCE OF ICING

Glaze is the ice deposit that is transparent, smooth, and dense (as high as 0.8 or 0.9 gm/cm^3)[1] in comparison to rime and hoarfrost. Supercooled moisture[2] contacting an exposed surface with its own temperature at or below 0° C when air temperatures are between 0° C and -3.9° C (25° F)[3] will freeze after the drops have spread and coalesced to form a tenacious coating of clear ice. A relatively "slow rate of freezing, large drop size, rapid rate of impingement, and slight supercooling favor glaze formation."[4] Hence, glaze is usually the product of freezing rain or drizzle.

Rime appears opaque and grainy in comparison to glaze and is less dense (as low as 0.2 to 0.3 gm/cm^3)[5]. Conditions conducive to its formation are similar to those for glaze, except that the temperatures of the exposed surface and/or the air are colder. In this case, the drops of moisture freeze more quickly and inhibit spreading and coalescing. Air pockets separate the frozen drops and create the grainy effect. Rime, too, is usually formed from freezing rain or drizzle.

Hoarfrost is obviously crystalline in appearance, with air spaces defined by delicate lacings of opaque ice. It is the least dense of the three types. It forms under temperature conditions similar to those for glaze and rime formation but the necessary moisture is supplied by humid air or water vapor. Usually, then, hoarfrost results from the sublimation of moisture in the ambient air. On some occasions, hoarfrost can also form on a cold surface that is introduced into warm, moist air—a circumstance not uncommon to an aircraft in flight.

Understandably, there are a number of weather types that can produce icing in these and mixed forms. In general, warm fronts with maritime tropical air overrunning continental polar air have the highest probability of producing glaze, but cold fronts and polar front waves are also considered to be frequent producers of icing from freezing rain or drizzle. In addition, icing can occur along stationary fronts or in weather types which have no frontal activity.

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1 Ralph E. Huschke, ed., *Glossary of Meteorology*, American Meteorological Society, Boston, Mass., p. 254, 1959.

2 Water that remains liquid below the "freezing" point, 0° C.

3 Iven Bennett, *Glaze, Its Meteorology and Climatology, Geographical Distribution, and Economic Effects*, Technical Report EP-105, Quartermaster Research and Engineering Center, Natick, Mass., p. 21, 1959.

4 *Ibid.*

5 Ralph E. Huschke, ed., *Glossary of Meteorology*, American Metereology Society, Boston, Mass., p. 483, 1959.

For purposes of this discussion, icing is considered as developing under two conditions which pose somewhat different problems for V/STOL aircraft: (1) icing at ground level, and (2) icing in the atmosphere.

1. Icing at Ground Level.[6]

a. Icing from Glaze Storms.

a. Icing from Glaze Storms. One of the more obvious producers of glaze and other forms of icing at ground level is the glaze storm. Freezing rain, among other precipitates, is distributed by the storm under conditions that allow glaze and rime to form on ground level surfaces. Such storms can be relatively small and can affect an area of only a few square miles; or they can be very large and cover a wide area as much as 600 miles in length. Amounts of ice produced vary with different storms, and even within one storm, due largely to local microclimates and the dynamic nature of the storm itself. Pure glaze deposits usually range in thickness from a trace to 2.5 inches or more, though unusual thicknesses of as much as 15 inches[7] are recorded. "Locations exposed to strong winds and in which temperatures are apt to be low during storms are most likely to receive heavy deposits."[8] Snow and other precipitates of the storm magnify the depth and damaging effects of the glaze. The duration of the ice may be a matter of several hours, several days, or more.

There is no universal synoptic meteorology of glaze storms. That is, a glaze storm may not always be associated with only one meteorological situation everywhere. However, these storms are usually the result of moist, mild maritime air overrunning dry, cold continental air in some frontal situation. However, freezing rain or drizzle can be produced in a nonfrontal situation at temperatures considerably below freezing (-30° C (-22° F)). In this case, the producing agent is usually supercooled stratus clouds (see section 2a).

Glaze storms occur most often across the middle latitudes east of the western mountains of North America, the higher middle latitudes of Europe and European USSR, and along the east coast of Japan. In the Southern Hemisphere, these storms are rare because there are no continental landmasses in the middle latitudes and, therefore, no mixing of cold continental air with mild maritime air.

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[6] The information in this section is largely summarized from Iven Bennett's *Glaze, Its Meteorology and Climatology, Geographical Distribution, and Economic Effects*, the most extensive collection of surface glaze and icing information available to date.

[7] G. A. McKay and H. A. Thompson, "Estimating the Hazard of Ice Accretion in Canada from Climatological Data," *Journal of Applied Meteorology*, Vol. 8, No. 5, p. 927, 1969.

[8] Iven Bennett, *Glaze, Its Meteorology and Climatology, Geographical Distribution, and Economic Effects*. Technical Report EP-105, Quartermaster Research and Engineering Center, Natick, Mass., p. 21, 1959.

The United States[9] experiences more glaze storms than any other country. They occur most frequently east of the Rocky Mountains "in a broad belt extending from north central Texas to southern New England"[10] as illustrated in Fig. 1. The greater part of this belt can expect at least one storm depositing from 0.25 to 0.50 inch of ice every 3 years as suggested in Figs. 2 and 3. Figure 4 gives an indication of the range of glaze thickness, its frequency, and its distribution.[11]

Glaze storms in the United States occur in the winter months when low temperatures prevail. Of course, inland areas and areas at higher latitudes experience the required low temperatures for a more extended length of time, allowing the glaze storm season to extend from November to March.

In Canada, the greatest number of glaze storms occur in the southern portion of the country from the Great Lakes to the Maritime Provinces. Because of higher latitudes, the glaze season is longer in Canada than in the United States. Glaze storms may be expected from September to June in the Prairie Provinces.

Europe commonly experiences glaze storms north of the wall of mountains formed by the Pyrenees and the Alps through Yugoslavia and the Balkan Mountains in Bulgaria. Austria, Switzerland, and Scandinavia report at least one glaze storm per year occurring most frequently in January. Ice deposits greater than 0.5 inch thick are unusual.

In western USSR, glaze storms are experienced north of a line connecting the northern shores of the Black, Caspian, and Aral Seas and south of the 60th parallel west of the Urals as illustrated in Fig. 5. The most frequent (1.0 to 5.9 storms/year) and most severe storms in terms of thickness (see Fig. 6) occur in the Ukraine and Don regions north of the Black Sea. The glaze storm season is typically November to March.

The eastern coast of Japan has meteorological similarities to the eastern coast of the United States, so it may be assumed that glaze storms occur in this part of the Far east.

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[9] The United States, as used in this report, refers only to the 48 contiguous states.

[10] Iven Bennett, *Glaze, Its Meteorology and Climatology, Geographical Distribution, and Economic Effects*, Technical Report EP-105, Quartermaster Research and Engineering Center, Natick, Mass., p 79.

[11] These maps seem to reveal areas of high glaze storm occurrence and ice thickness in the California mountains outside of the glaze belt. Bennett observes that these concentrations of ice are not the results of true glaze storms but rather the consolidation of other rime and wet snow deposits after thawing and refreezing.

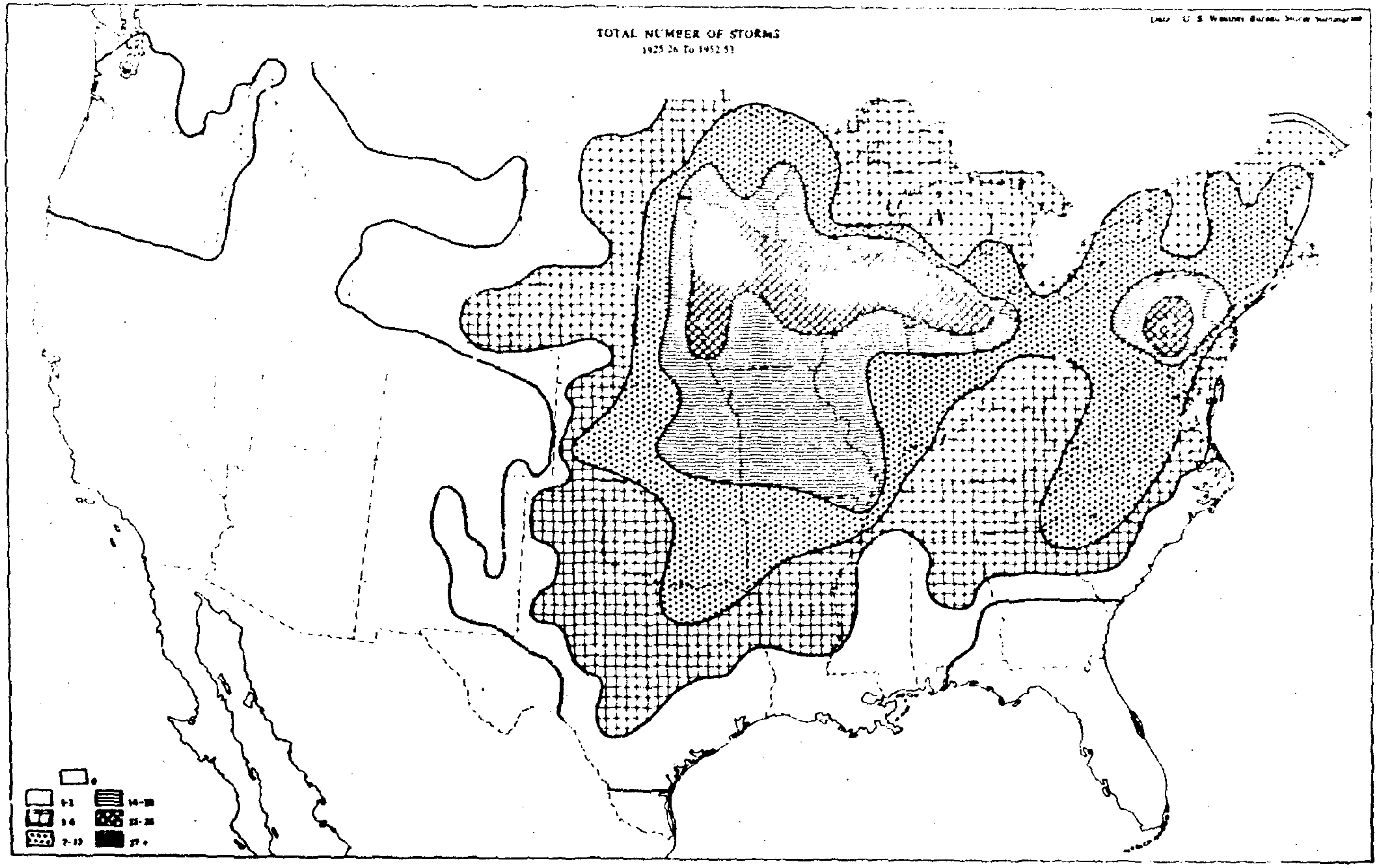

Fig. 1. Total number of glaze storms for a 28-year period–USA. (Ending with the winter of 1952-53, as reported in "Storm data and unusual weather phenomena," *Climatological Data, National Summary*, U. S. Weather Bureau. (Before 1950, these storm reports appeared in the *Monthly Weather Review* under the title "Severe Local Storms.") Source: I. Bennett, *op. cit.*
Note: Bennett suggests map be used with caution due to data limitations.

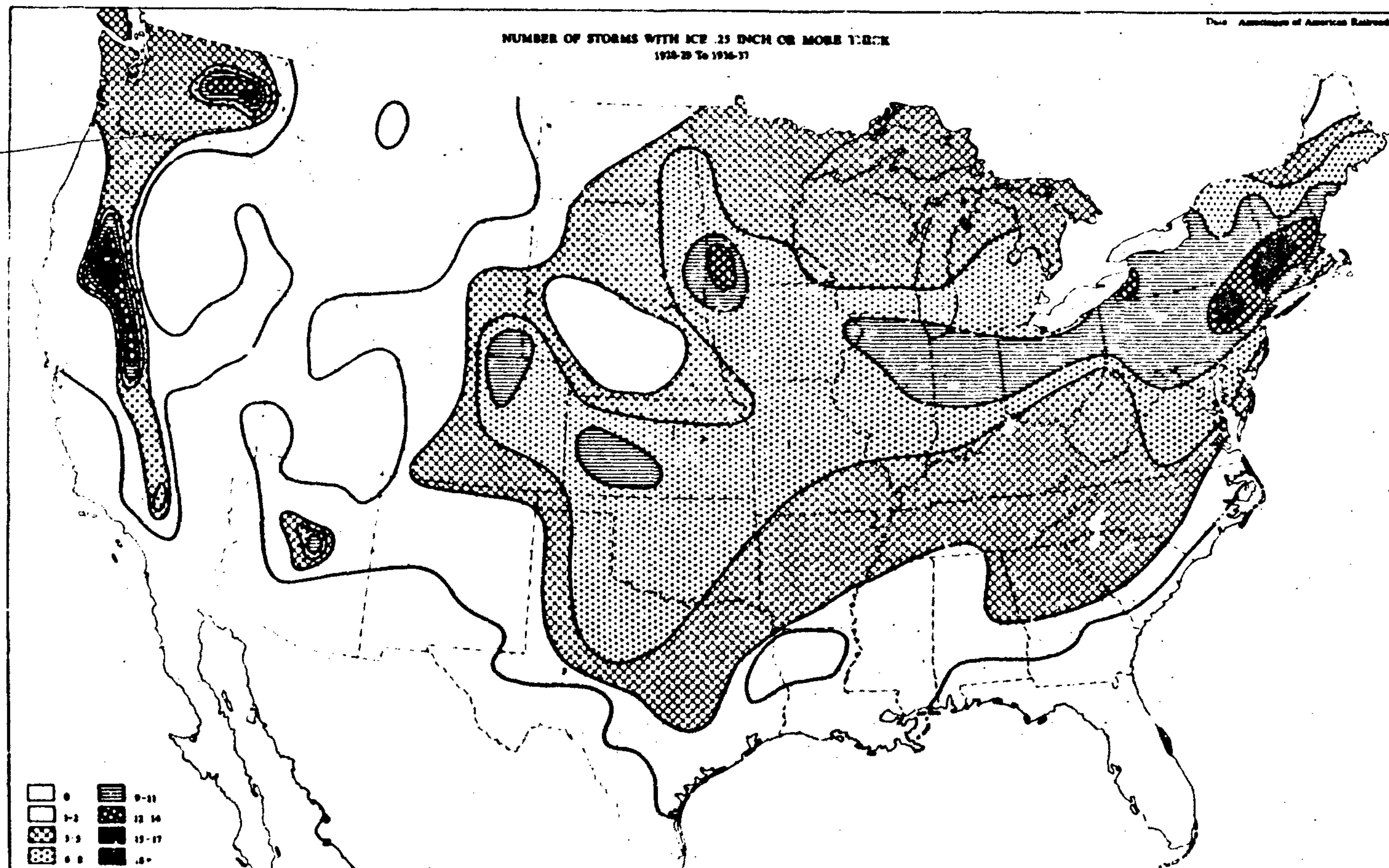

Fig. 2. *Number of storms with ice 0.25 inch or more thick*–USA. (*Observed during the 9-year period of the Association of American Railroads study (undated). Note that the Columbia River gorge area, in which thick glaze is fairly common, does not show up as an area of high frequency on this map.) Source: I. Bennett, *op. cit.*

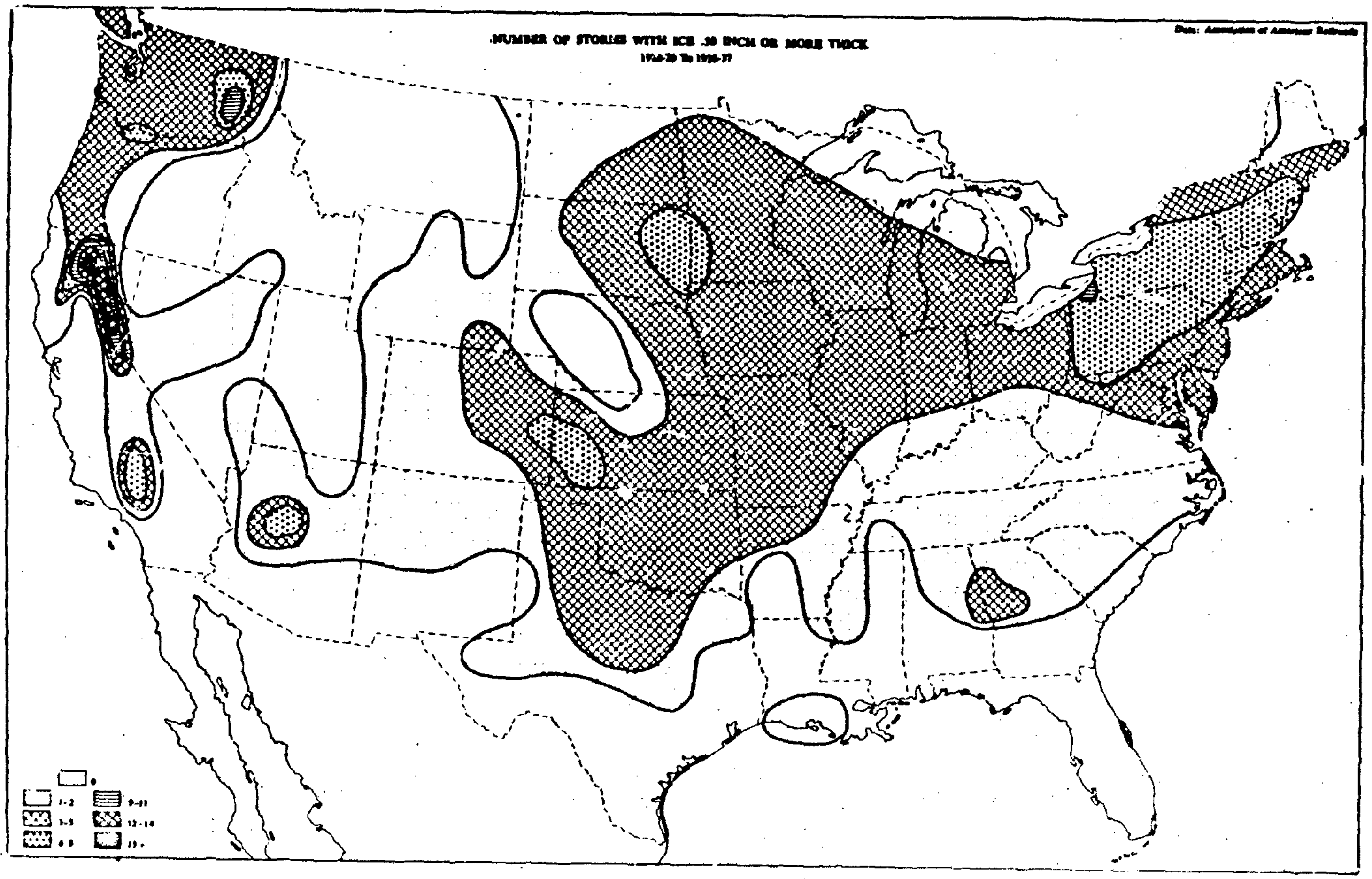

Fig. 3. Number of storms with ice 0.50 inch or more thick--USA. (Observed during the 9-year period of the Association of American Railroads study.) Source. I. Bennett, *op. cit.*

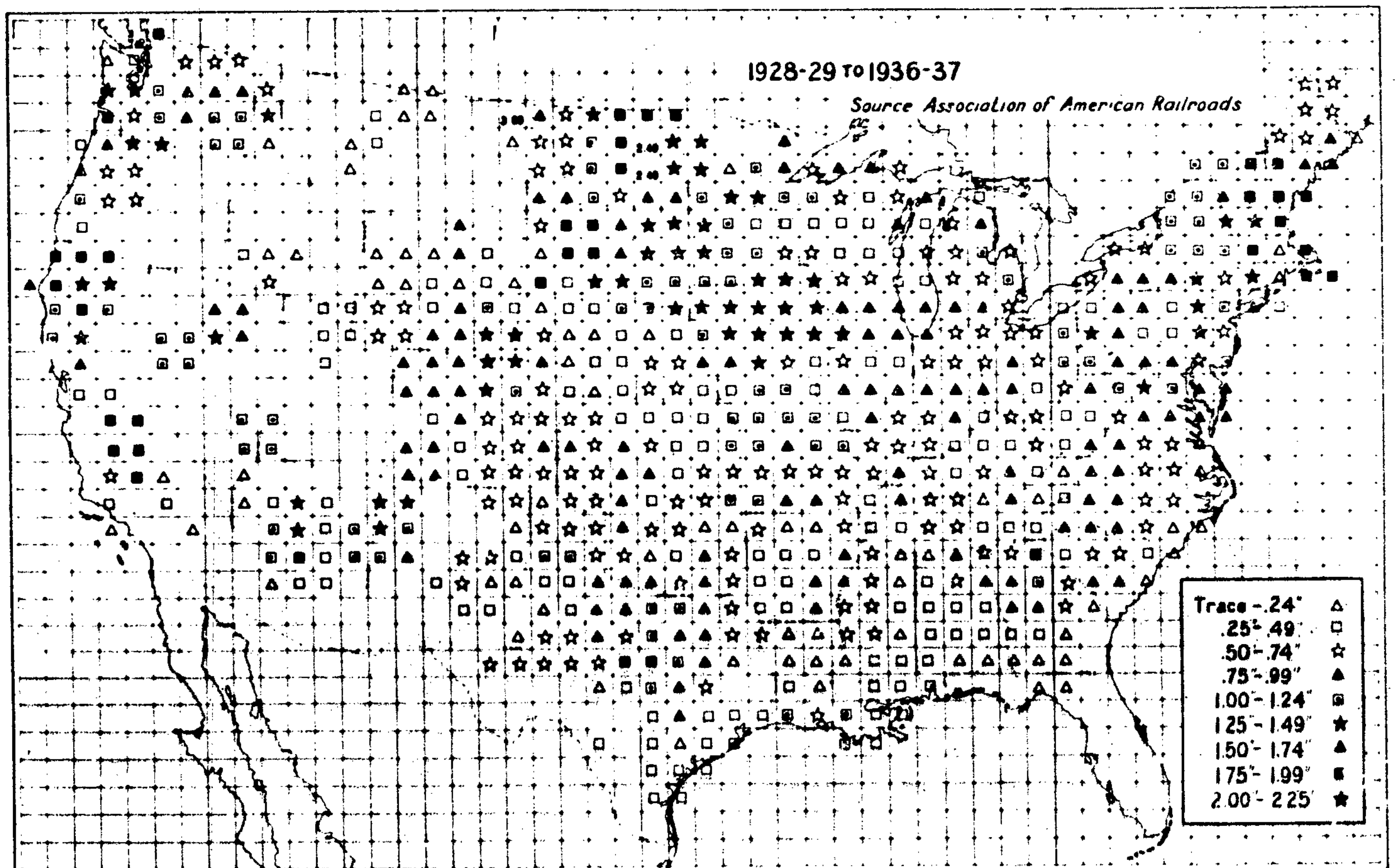

Fig. 4. Extreme radial thickness of glaze on utility wires—USA. (Greatest thickness of ice observed in each grid square during the 9-year period of the Association of American Railroads study.) Source: I. Bennett, *op. cit.*

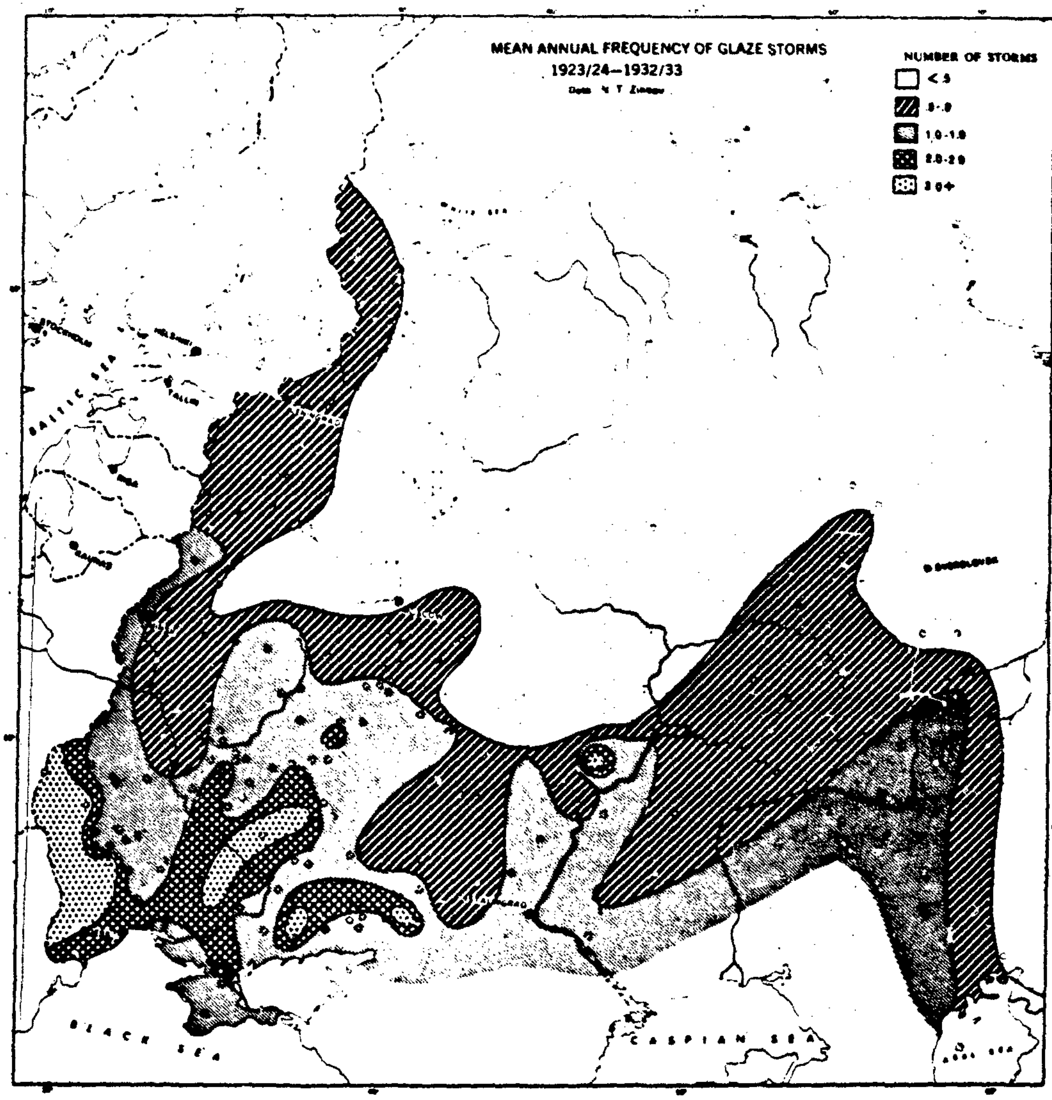

Fig. 5. Mean annual frequency of glaze storms—USSR. (European section of the USSR for the 10-year period from 1923-24 to 1932-33. Based on data obtained from N. T. Zikeev.) Source: I. Bennett, *op. cit.*

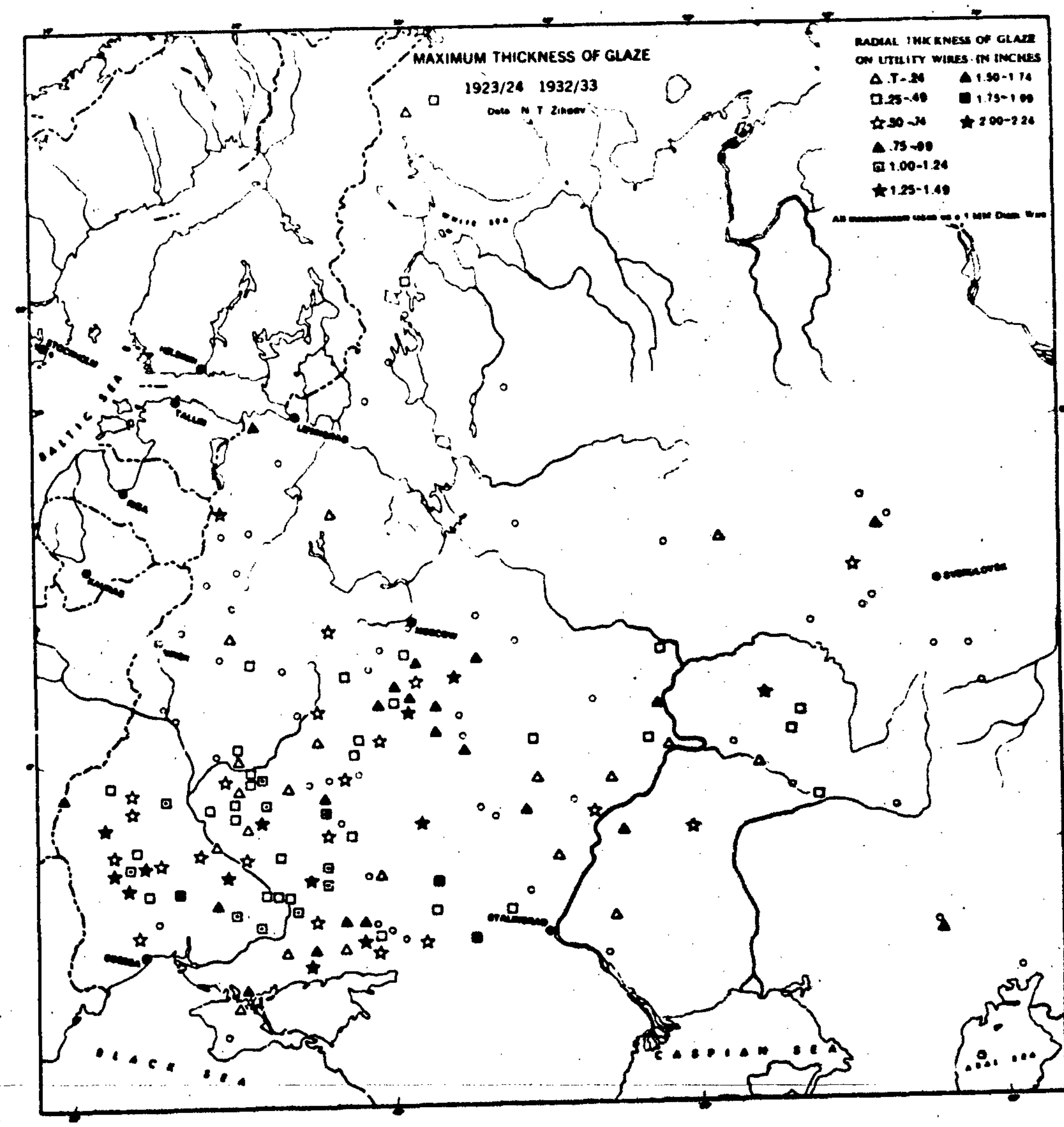

Fig. 6. Maximum thickness of glaze—USSR. (At various locations in the European portion of the USSR during the 10-year period 1923-24 to 1932-33. Based on data obtained from N. T. Zikeev.) Source: I. Bennett, *op. cit.*

b. Icing from Fog and Sublimation. Water droplets suspended in a heavy fog with a temperature near but above 0° C may form glaze upon contacting a sufficiently cold, exposed surface. If the fog is supercooled, there is a greater chance that ice as rime will form; and the colder the surface, the greater is the chance that rime will form instead of glaze. In mountain regions, ice developing from fog will generally be rime rather than glaze.

Figures 7 through 10 illustrate the worldwide distribution of the frequency of occurrence of supercooled fog. The isolines (lines of equal frequency of occurrence) are aligned latitudinally and shift seasonally.

In the Northern Hemisphere, supercooled fog is most often present in winter affecting most of North America, Europe, Asia, and, especially, the USSR (Fig. 7). By summer, the supercooled fog has retreated poleward affecting only the Arctic Ocean and its land margins.

In the Southern Hemisphere, land areas north of the Antarctic are relatively unaffected by supercooled fog except possibly in the winter months represented by July in Fig. 9. Latitudinal shift of the fog is minimal compared to that of the Northern Hemisphere.

The variations in the configuration of isolines reflect numerous physical influences such as the landmass-maritime relationships, surface morphology, and elevation. The significance of such influences, especially that of elevation, is apparent along the western coast of South America where isolines encompass the Andes Mountains.

Very humid air with a dewpoint from slightly above to below 0° C can also produce glaze, rime, or hoarfrost if it should come in contact with an exposed surface at a temperature below 0° C inducing sublimation. Rime, or sometimes glaze, will usually develop under these conditions when the dewpoint is slightly above 0° C; while hoarfrost will develop when the dewpoint is below 0° C. Greater amounts of ice will develop when surface temperatures are low and specific humidity of the air is high. "Ice resulting from such a situation is encountered most commonly along seacoasts and the margins of such large inland bodies of water as the Great Lakes, but it also is sometimes observed on roads near small lakes and ponds."[12]

Moist air or heavy fog in mountain regions under properly cold conditions will often meet the above requirements for ice formation but especially those for rime formation. Therefore, rime can be expected to occur relatively frequently in the

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[12] Iven Bennett, *Glaze, Its Meteorology and Climatology, Geographical Distribution, and Economic Effects*, Technical Report EP-105, Quartermaster Research and Engineering Center, Natick, Mass., p. 134.

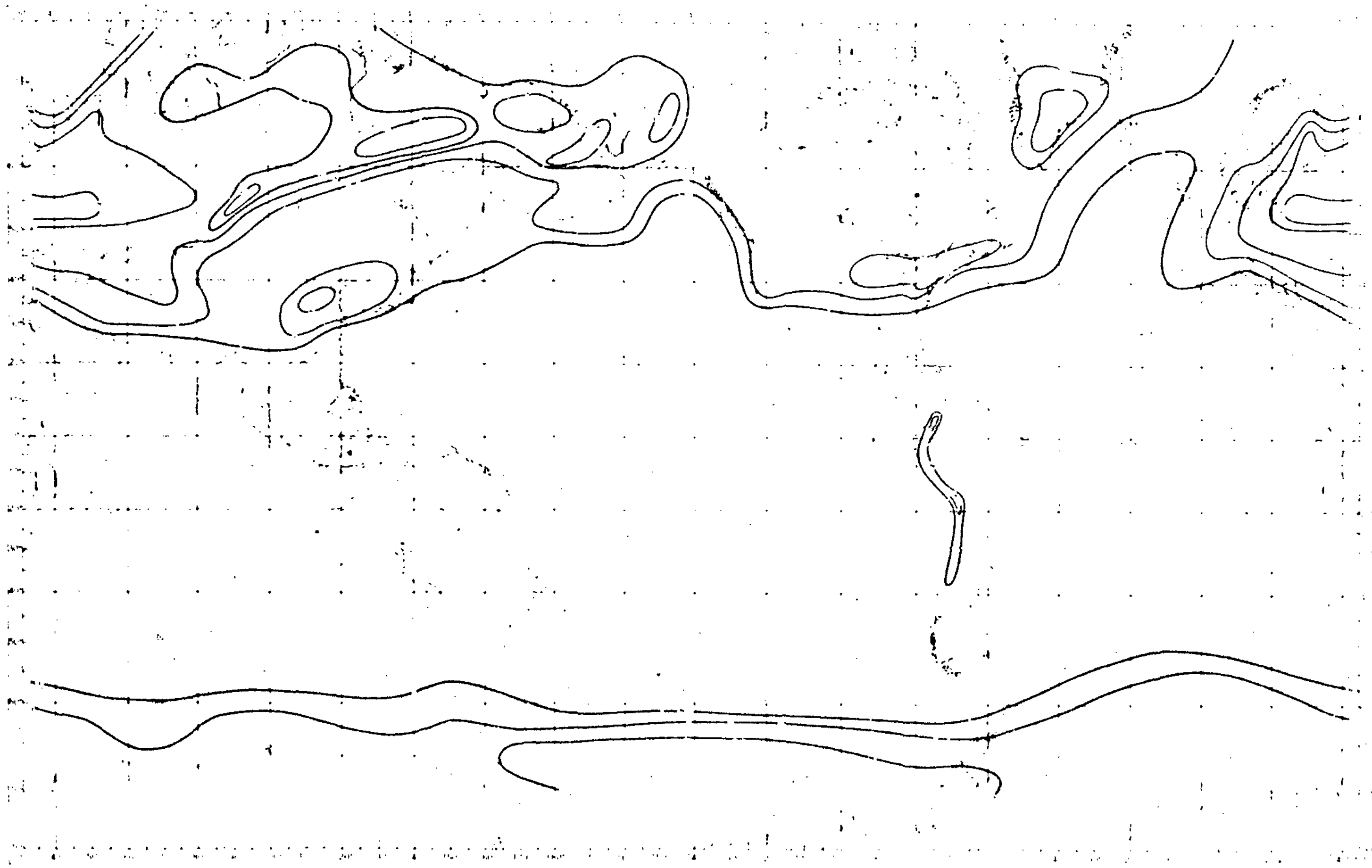

Fig. 7. Percentage frequency of occurrence of supercooled fog—January—worldwide. Source: N. B. Guttman, U. S. Naval Weather Service Command, *Study of Worldwide Occurrence of Fog, Thunderstorms, Supercooled Low Clouds and Freezing Temperatures*, Asheville, NAVAIR 50–1C–60, 1974.

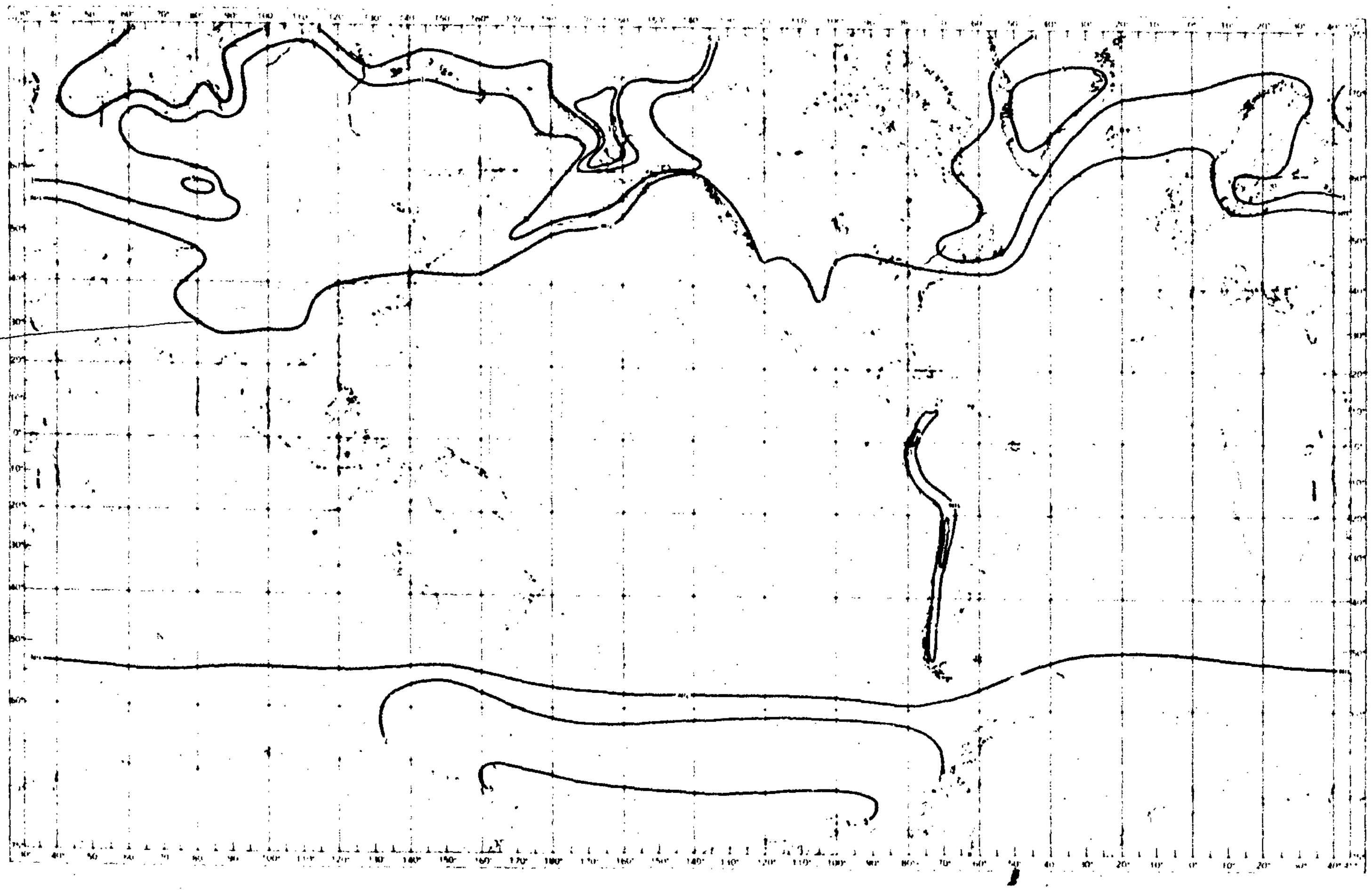

Fig. 8. Percentage frequency of occurrence of supercooled fog—April—worldwide. Source: N. B. Guttman, *op. cit.*

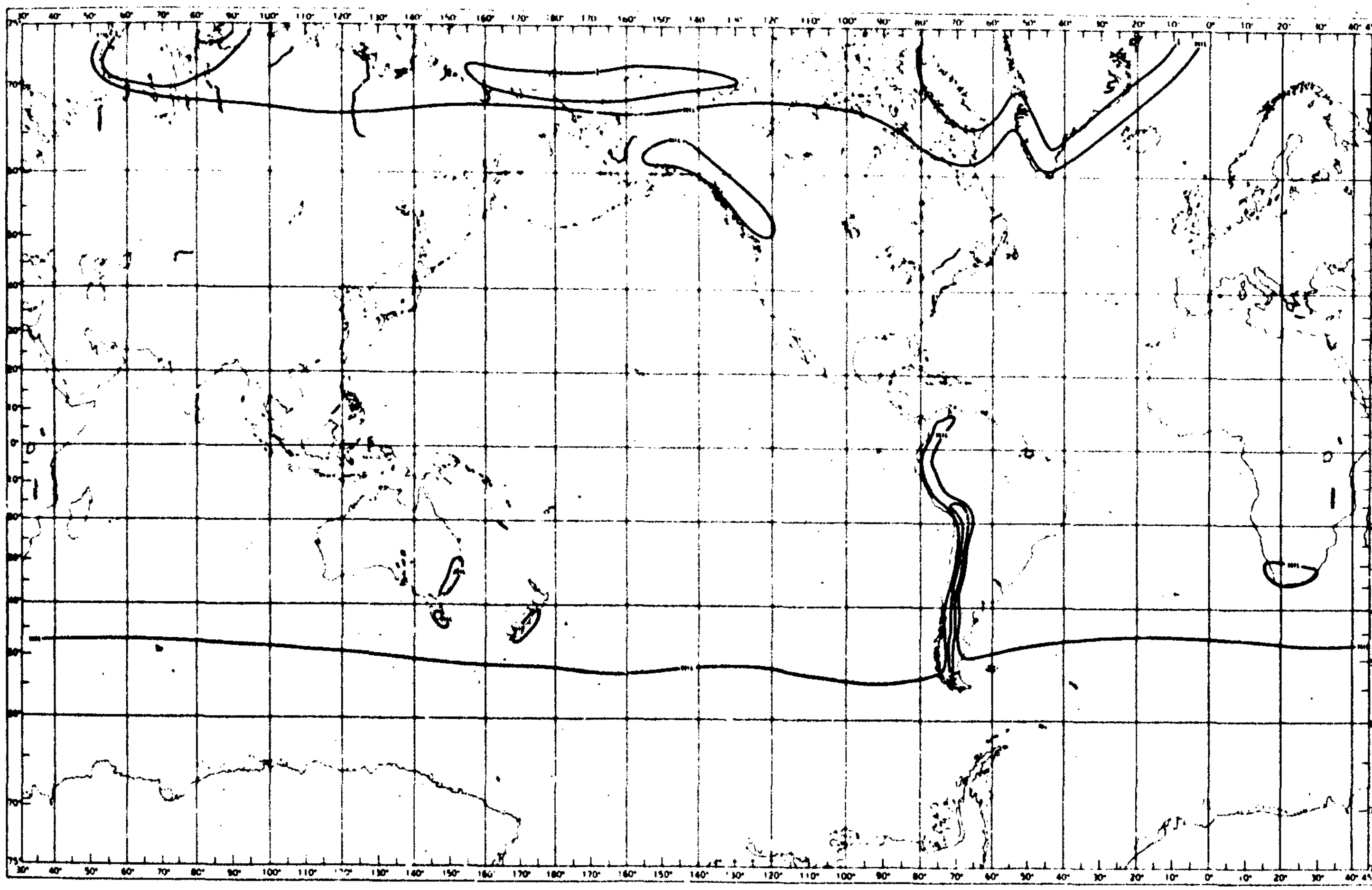

Fig. 9. Percentage frequency of occurrence of supercooled fog–July–worldwide. Source: N. B. Guttman, *op. cit.*

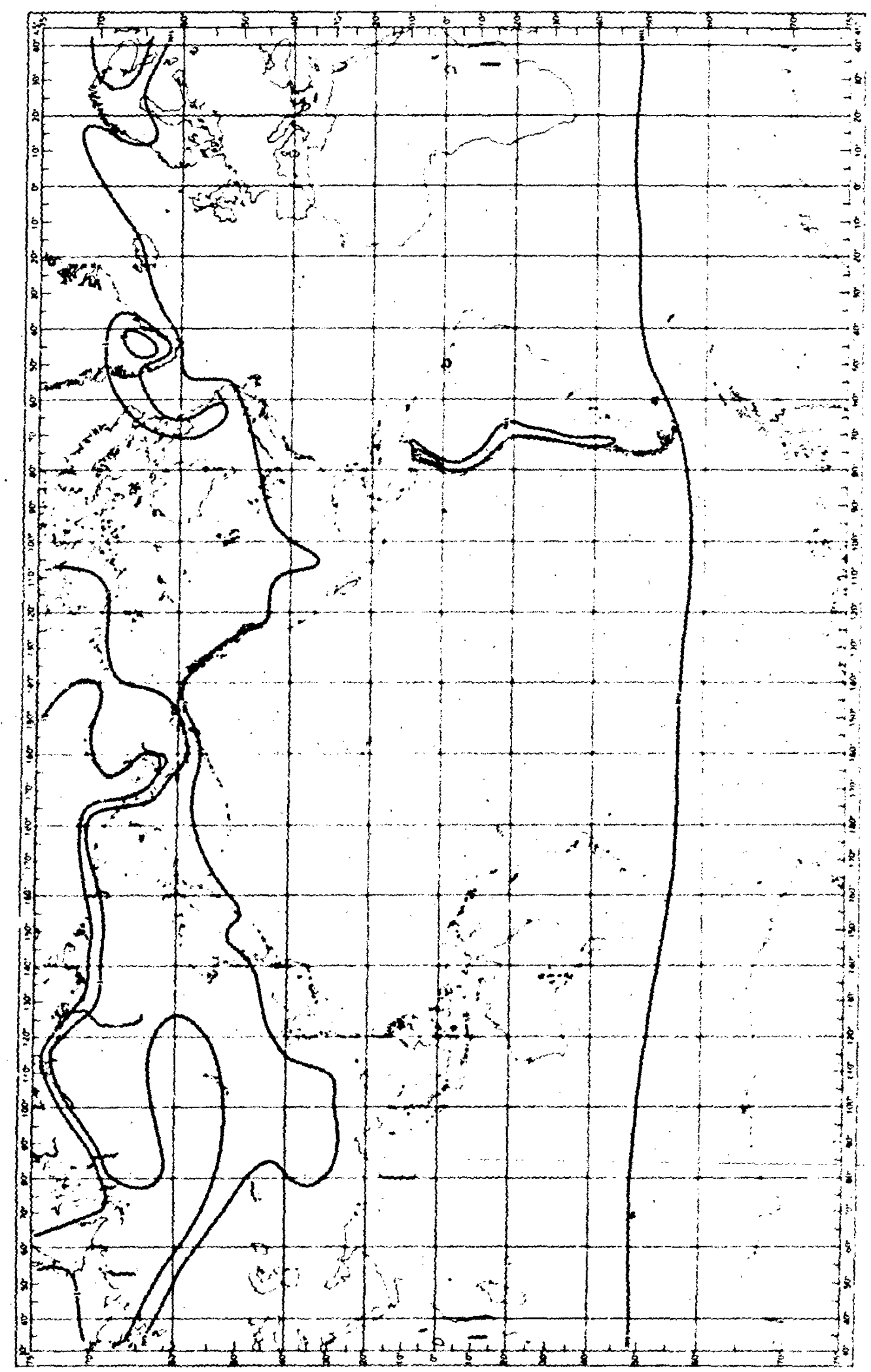

Fig. 10. Percentage frequency of occurrence of supercooled fog–October–worldwide. Source: N. B. Guttman, *op. cit.*

mountains of western Europe, the Caucasus in the USSR, the western coastal mountains of North America (the Cascades, Sierra Nevadas, the Coastal Ranges), the northeastern coastal mountains of North America (northern Appalachians), the Atlas Mountains of North Africa, the mountains in southern Chile, and the mountains in southwestern New Zealand.[13] Additionally, the mountains of Eastern Siberia, south central USSR, and the northern Urals experience rime frequently.[14]

Frequency, thickness, and duration of these rime deposits vary in accordance with the many unique physical factors associated with each specific place and the physical nature of the affected surface. Generalizations are difficult. Frequencies can range from a few daily occurrences per year to more than 40; thickness can vary from a trace to more than a foot in diameter; and duration of the ice can range from a few hours to several days.

Since areas with temperatures slightly above, at, or below 0° C located near moisture sources are areas of potential icing occurrence, Figs. 11 through 14 are included to indicate those areas of the world seasonally affected by 0° C temperatures at the surface level and to indicate the greater areal extent of freezing temperatures with increasing elevation or altitude.

c. **Icing from Thawing and Refreezing.** Another natural contributor to the formation of icing, glaze in particular, is the action of thawing and subsequent refreezing of deposited rime, fallen snow, or similar precipitates. Such activity depends on so many factors that predictions as to its time and place of occurrence are virtually impossible to make.

2. Icing in the Atmosphere.

a. **Icing in Clouds.** Icing is probably more often encountered in the atmosphere than at the surface simply because freezing temperatures, as a function of altitude, and cold moisture derived from clouds, are more often available. Glaze and rime icing are encountered at all latitudes when stratiform clouds, which extend above the freezing level (see Figs. 11 through 14), and which contain supercooled moisture, exist. Glaze or mixed forms of ice usually develop from cumuliform clouds, and rime or mixed forms develop from stratiform clouds. When these clouds are associated with

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[13] Iven Bennet: *Glaze, Its Meteorology and Climatology, Geographical Distribution, and Economic Effects,* Technical Report EP-105, Quartermaster Research and Engineering Center, Natick, Mass. p. 112.

[14] Library of Congress, Washington, D. C. Aerospace Technology Division, *Glazed Frost and Ice Formation on Cables within the Territory of the USSR* (unedited trans. of Gololed i abledeneniye provodov na territorii SSSR, by A. V. Rudneva, 1961) Report No. ATD-U-64-47, 1964, p. 242-260.

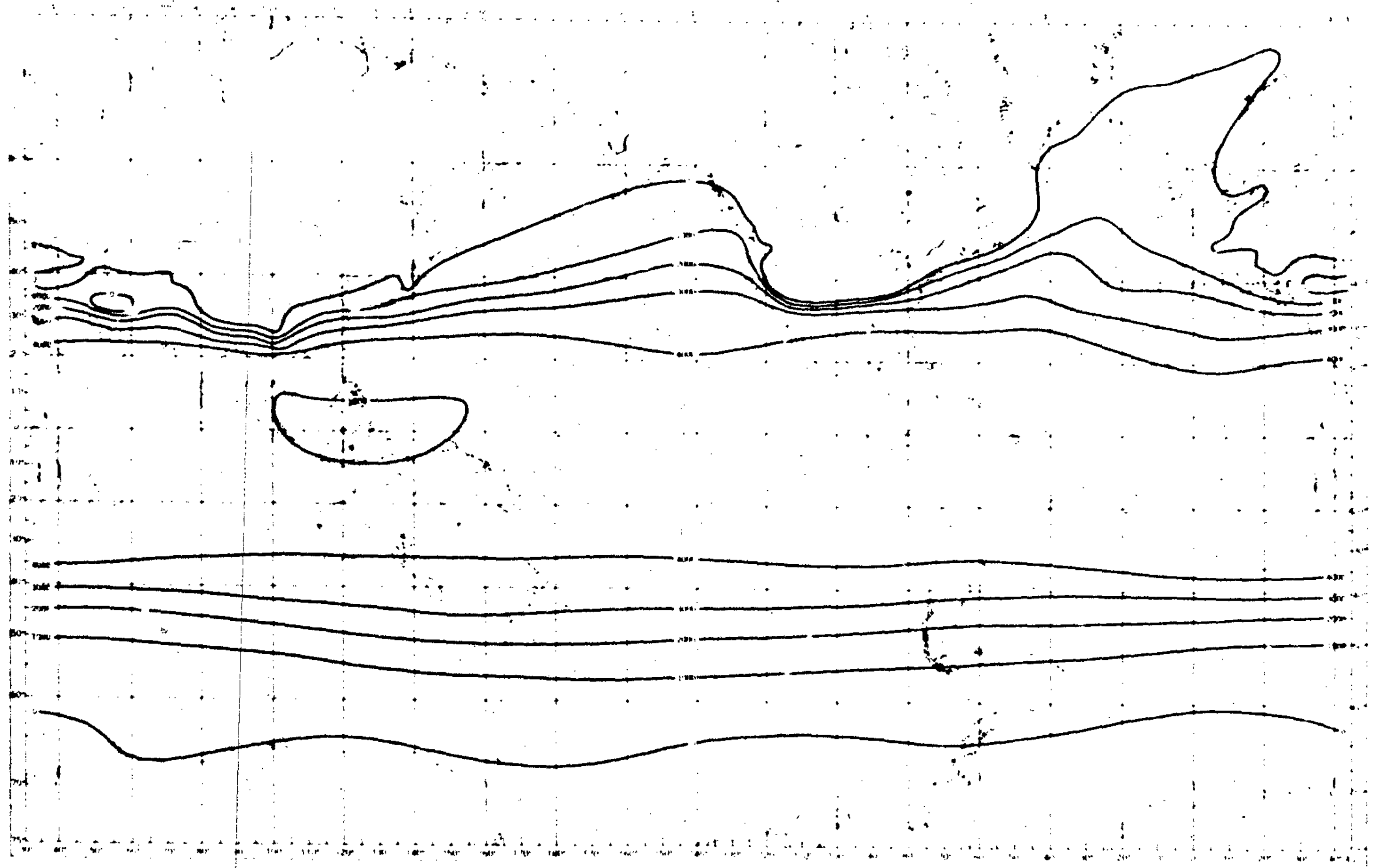

Fig. 11. Average height of the freezing level (meters) Dec Jan Feb - worldwide. Source: N. B. Guttman, op. cit.

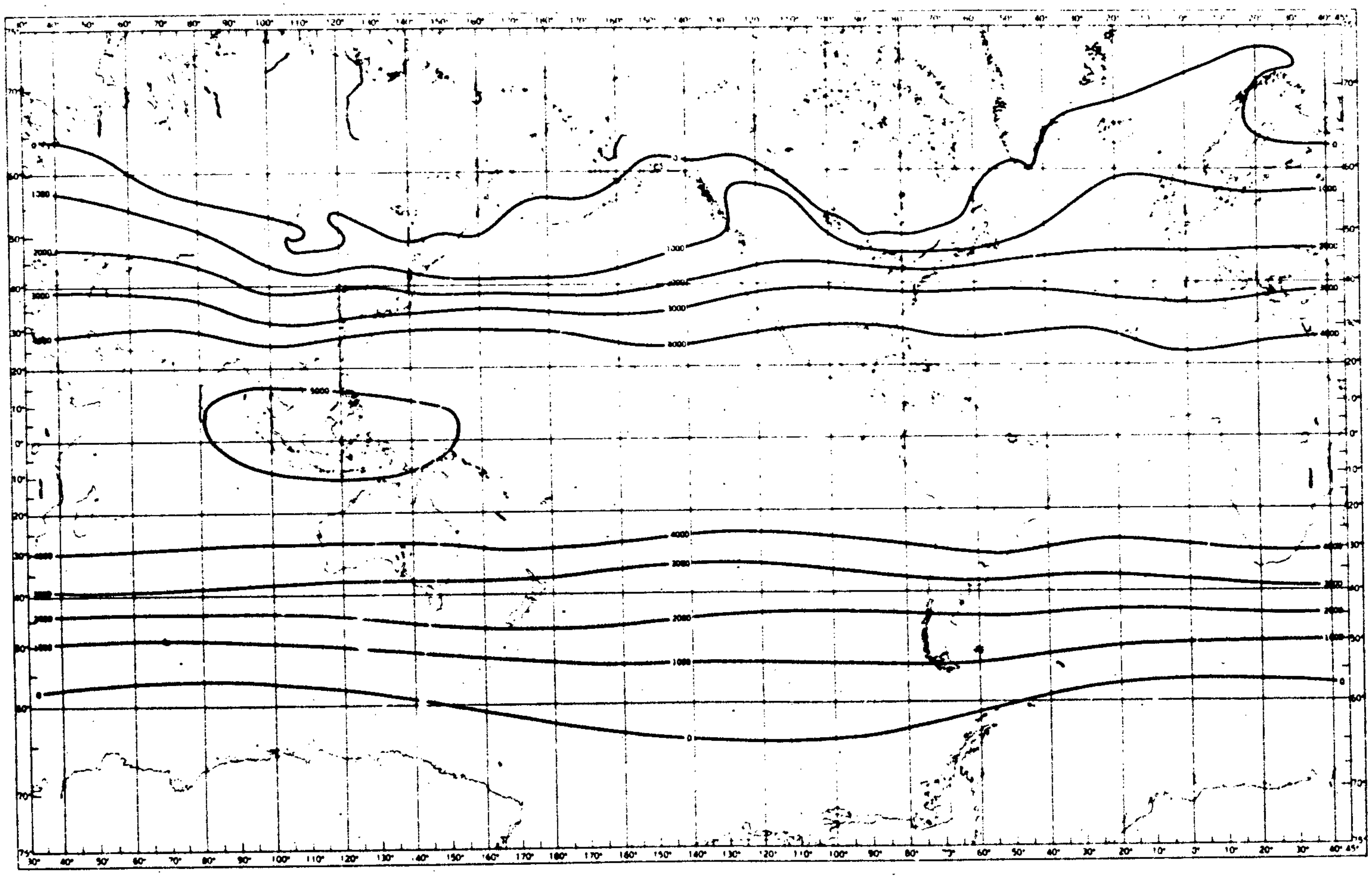

Fig. 12. Average height of the freezing level (meters)–Mar–Apr–May–worldwide. Source: N. B. Guttman, *op. cit.*

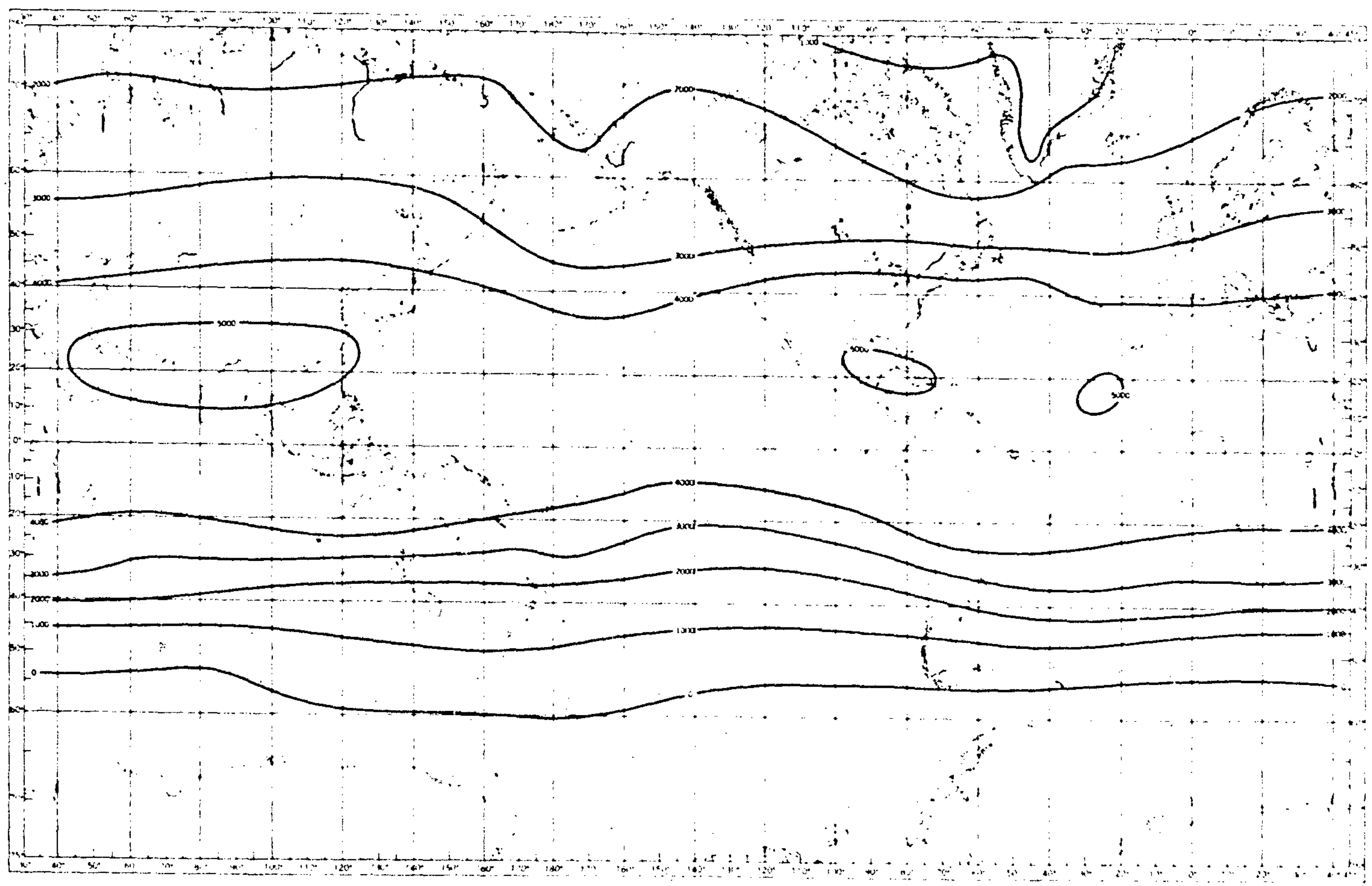

Fig. 13. Average height of the freezing level (meters)--Jun--Jul--Aug--worldwide. Source: N. B. Guttman, op. cit.

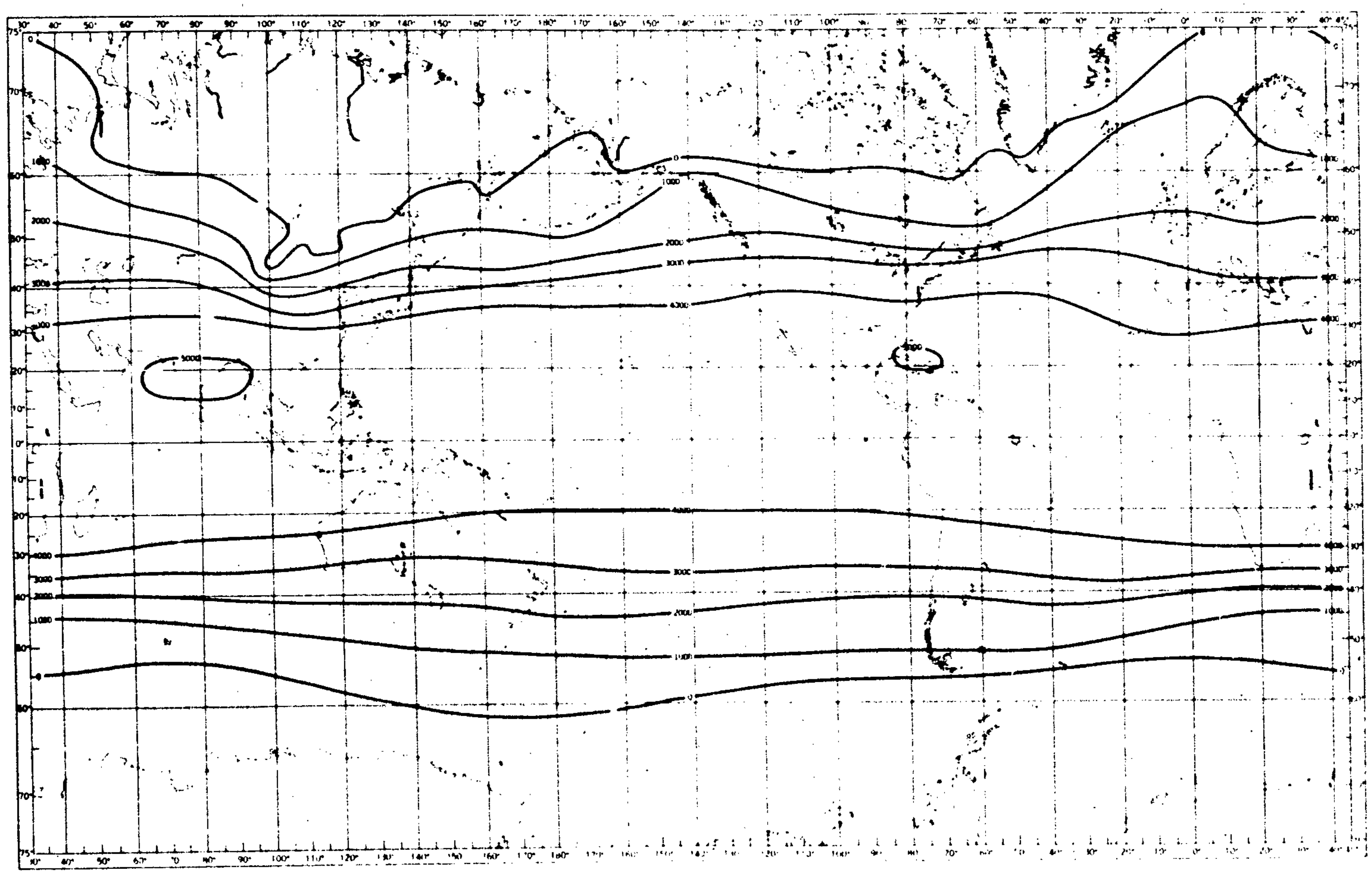

Fig. 11. Average height of the freezing level (meters)–Sep–Oct–Nov–worldwide. Source: N. B. Guttman, *op. cit.*

frontal systems, the probabilities of icing are increased. Flight through liquid precipitation falling from these clouds when air temperatures are below freezing can also produce icing.

Figures 15 through 18 show the seasonal distribution of the percentage frequency of occurrence of supercooled stratus and low cumulus clouds for most of the world. The Southern Hemisphere exhibits a latitudinal orientation of isolines that shifts little throughout the year. Supercooled stratus and low cumulus clouds appear less than 5 percent of the time over the land areas except for the southern tip of South America in winter (June, July, August) and spring (September, October, November) when they appear between 5 percent and 25 percent of the time (Figs. 17 and 18). The highest percentage of frequency of occurrence (more than 25 percent) exists over the waters surrounding the Antarctic throughout the year.

In contrast, the isolines for the Northern Hemisphere create cellular patterns reflecting the different landmass-maritime relationship. Winter (December, January, February) is generally the season of highest frequencies and greatest continental extent of the phenomena (Fig. 15). Occurrences of more than 25 percent frequency are associated with the Canadian Maritimes, Iceland, the Baltic Sea area of Europe and the USSR, the northeast Asian coast, and the western coast of Alaska. The greatest frequencies of occurrence (more than 50 percent) for either hemisphere occur in cells over the North Pacific in winter (December, January, February) and spring (March, April, May) as illustrated in Figs. 15 and 16. However, the Arctic regions experience greater frequencies in summer (June, July, August, Fig. 17), and the northern continental areas, especially northern North America and northern Siberia, experience greatest frequencies of occurrence of these clouds in autumn (September, October, November, Fig. 18).

b. Icing from Combined Factors. As a general rule, icing (glaze, rime, or hoarfrost) can be expected to occur within the first 30,000 feet of the troposphere when temperatures fall between freezing and -40° C (-40° F) and when the dewpoint spread[15] is usually less than 6 C° (10.8 F°),[16] as illustrated in Fig. 19. USAFETAC devised a method for determining the probability of encountering icing at four pressure surfaces for specific stations in the Northern Hemisphere from which isoline analyses were made. Selected maps representing the midseason months (Figs. 20 through 35) were based on several assumptions of which the following are particularly significant:

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[15] "Dewpoint spread" is defined as the difference between the dewpoint and air temperature.

[16] US Air Force, *Weather Forecasters' Guide on Aircraft Icing*, Air Weather Service Manual 105-39, 1969, p. 4-1, and p. A1-4.

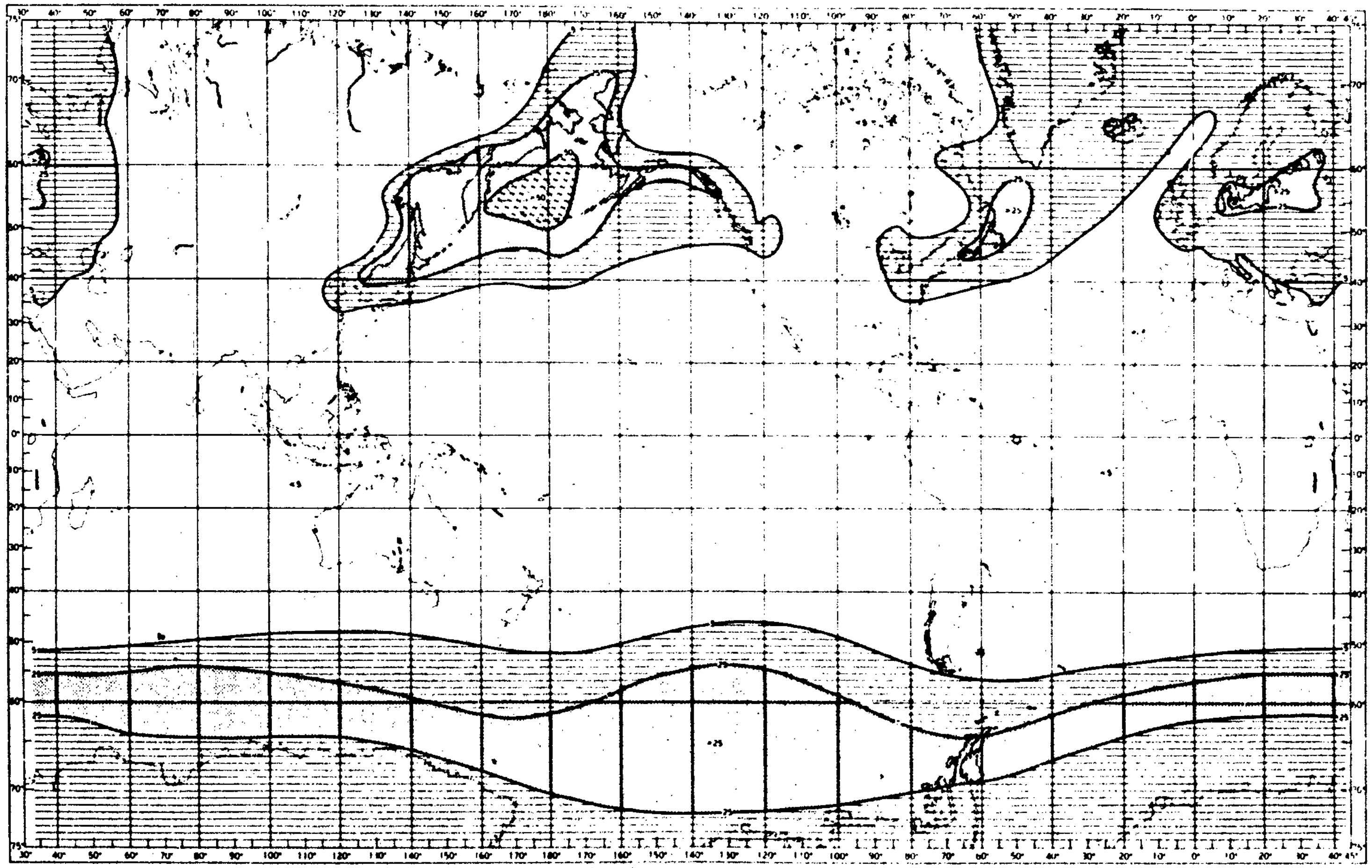

Fig. 15. Percentage frequency of occurrence of supercooled stratus and low cumulus–Dec–Jan–Feb–worldwide.
Source: N. B. Guttman, *op. cit.*

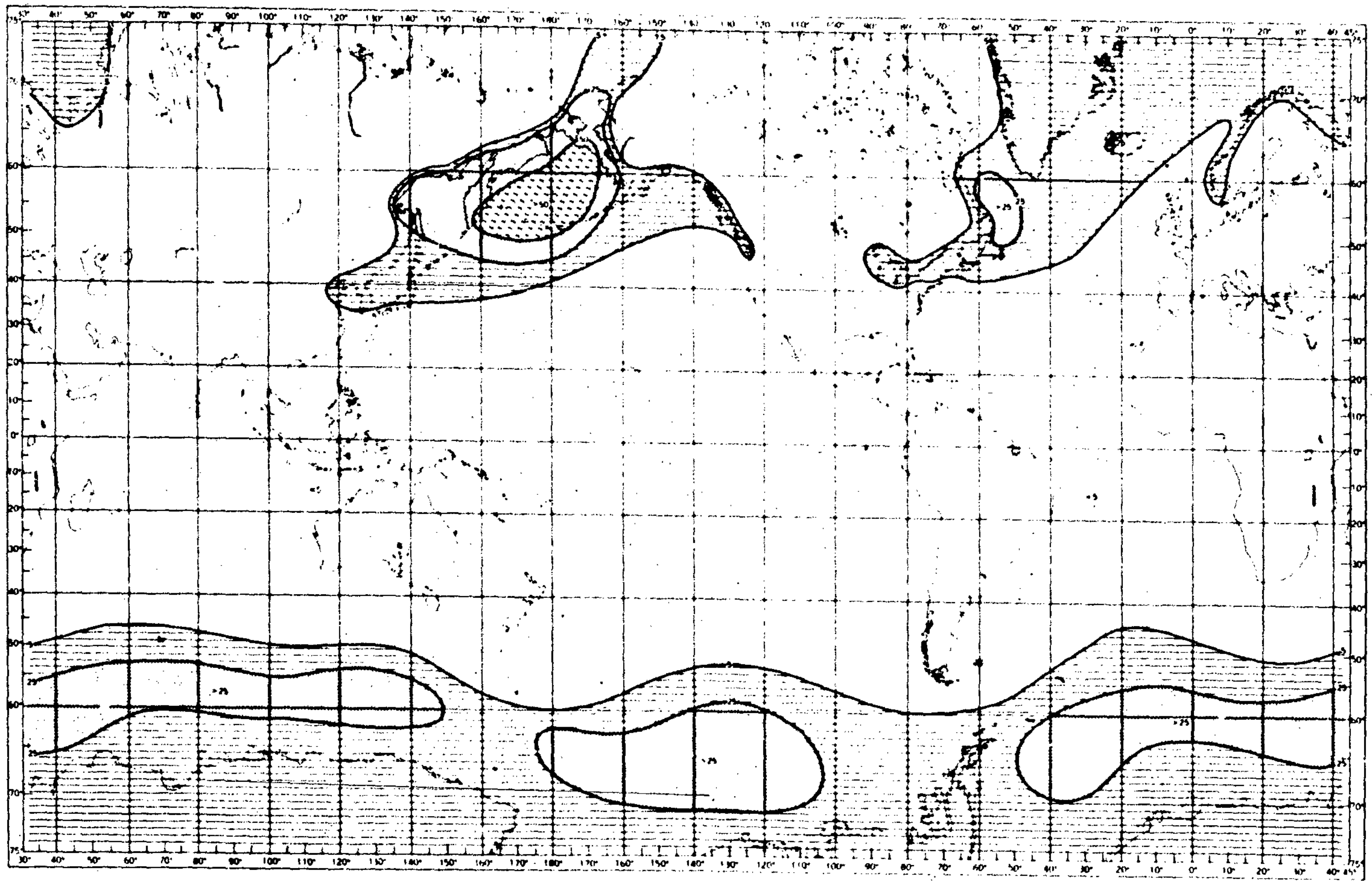

Fig. 16. Percentage frequency of occurrence of supercooled stratus and low cumulus—Mar–Apr–May—worldwide.
Source: N. B. Guttman, *op. cit.*

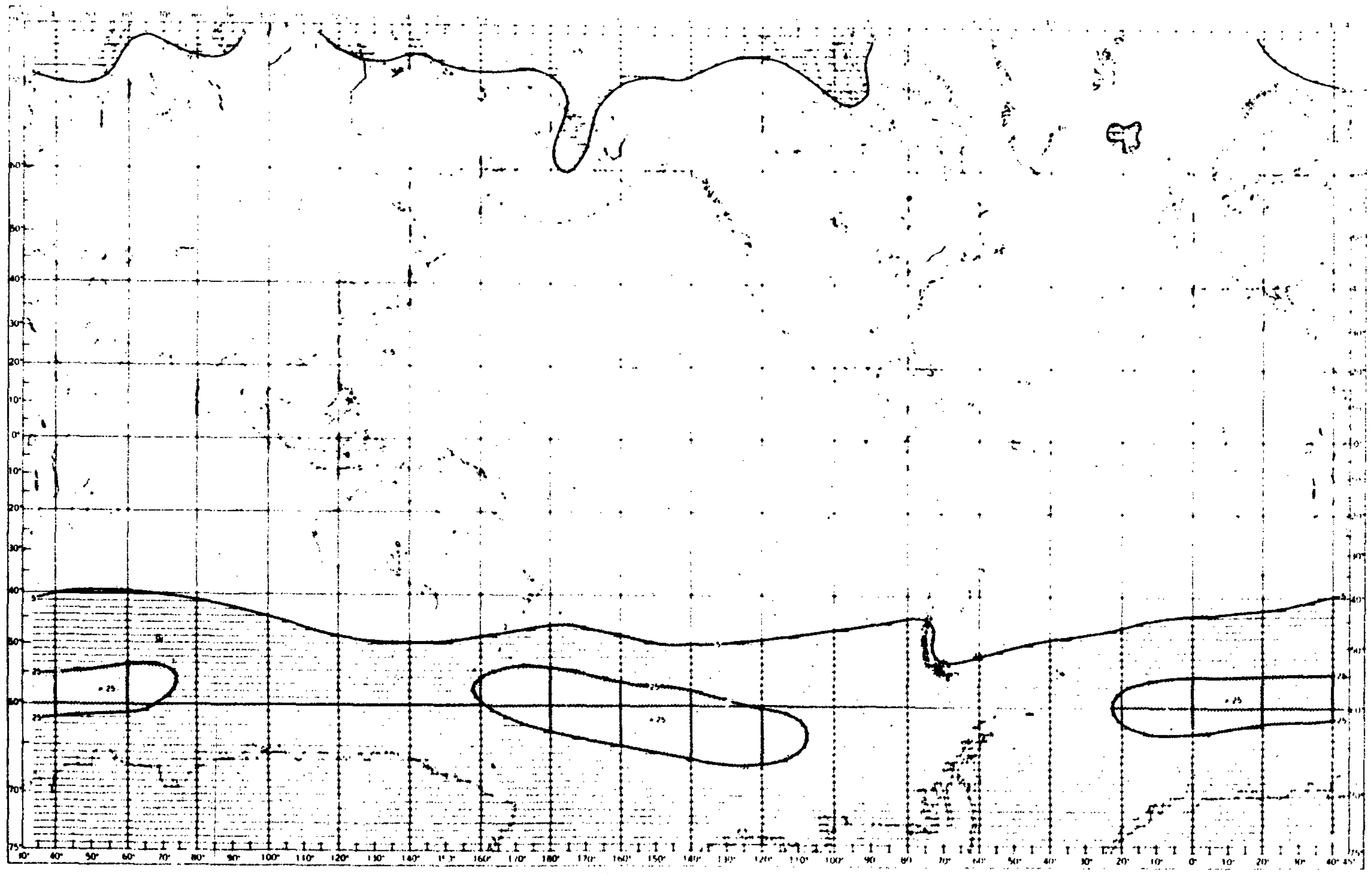

Fig. 17. Percentage frequency of occurrence of supercooled stratus and low cumulus—Jun–Jul–Aug–worldwide.
Source: N. B. Guttman, *op. cit.*

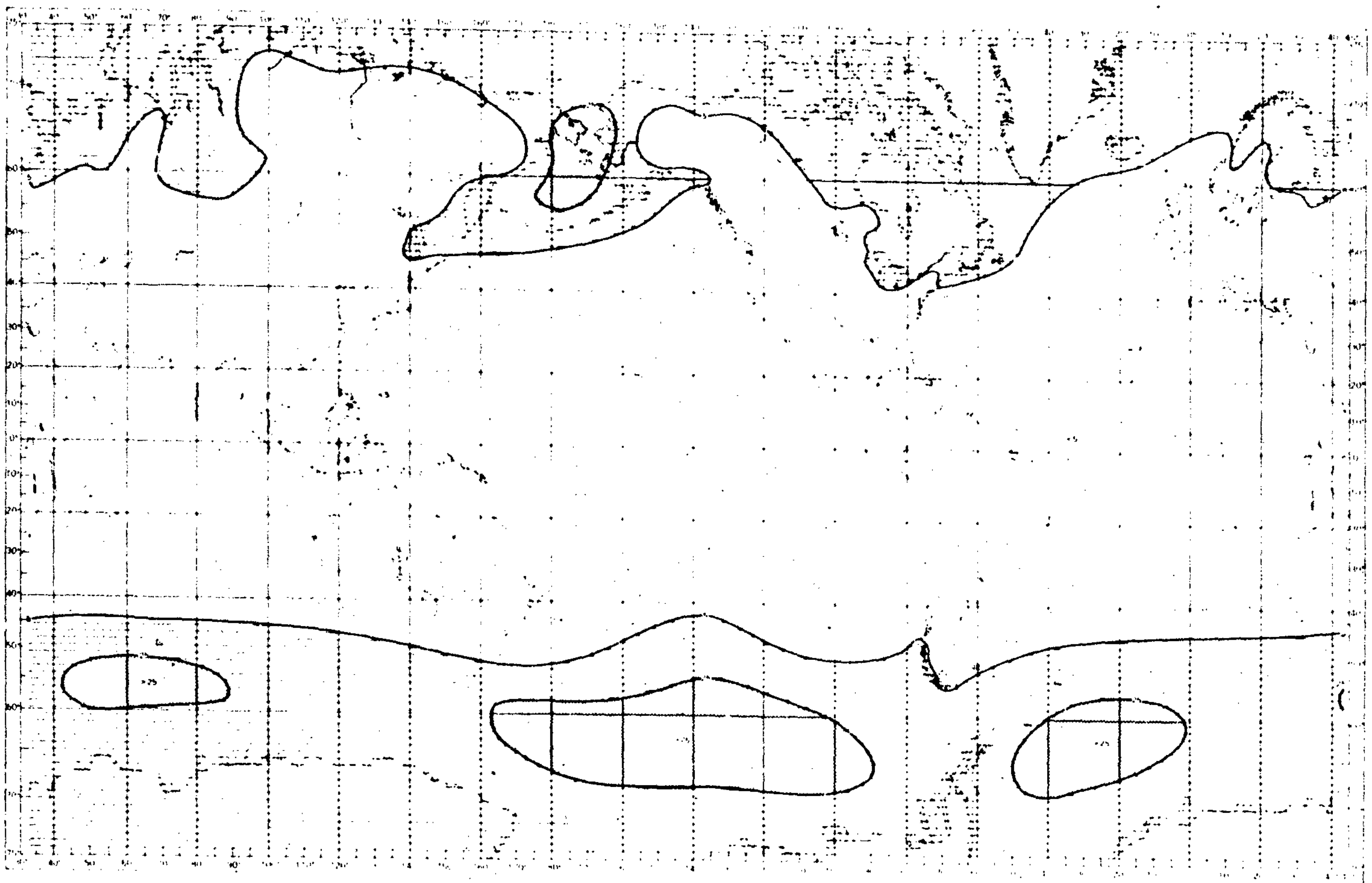

Fig. 18. Percentage frequency of occurrence of supercooled stratus and low cumulus Sep Oct Nov, worldwide.
Source: N. B. Guttman, *op. cit.*

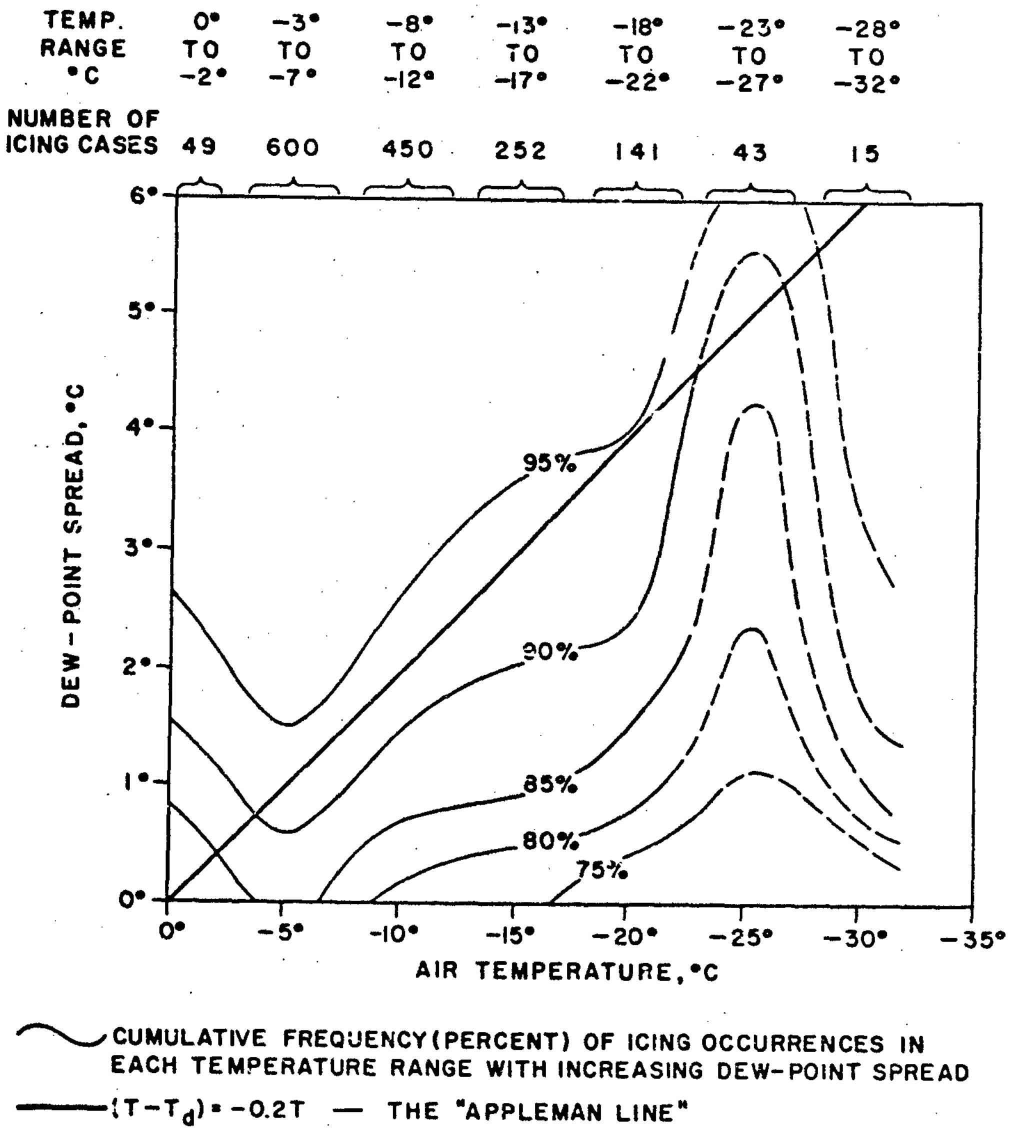

Fig. 19. Graph of cumulative frequency of icing occurrences as functions of temperature and dewpoint spread. Source: *Forecaster's Guide on Aircraft Icing*, Air Weather Service Manual, AWSM 105-39, 7 January 1969, Attachment 1.

(1) Icing will usually occur between -3° C (26.6° F) and -30° C (-22° F) due to "the heat of friction across the airframe,"[17] and the fact that "supercooled water rarely exists at temperatures colder than -30° C."[18] in nature.

(2) Icing rarely occurs at altitudes higher than 20,000 feet above Mean Sea Level except when cumuliform clouds occasionally build up to greater heights.

To further define the icing limits, studies revealed that the majority of icing cases occur between -3° C (26.6° F) and -12° C (10.4° F) inclusive with a dewpoint spread near 2 C° (3.6 F°) or less (see Fig. 19).[19]

Accordingly, it would be expected that the probability of encountering icing conditions is greatest in winter and least in summer, both in terms of value and areal extent. For the lower pressure surfaces, 1000 millibars (mb), 850 mb, and 700 mb (see Table for linear equivalents), this conclusion is substantiated by Figs. 20 through 22 and 28 through 30. However, by the time the 500-mb surface is reached, the pattern is reversed. At that level, icing is limited to low percent probabilities in a narrow midlatitude band in the winter (Fig. 23) which develops by summer into a complex pattern encompassing sections of equatorial latitudes and combining the highest percent probabilities with their greatest areal extent for the year (Fig. 31).

Increasing icing probabilities and extension of their incidence southward would seem to be directly related to increasing altitude. This assumption is verified through the 850-mb level, but this level yields the highest percent probability for the year at any level (25 percent over Japan in winter, Fig. 21). At the 700-mb level, the iscline gradients become more gentle and the probability of icing rarely exceeds 10 percent. The southerly extension of icing continues, however. These tendencies continue at the 500-mb level. At the higher levels, then, the temperatures drop below the optimum range for icing conditions, and available moisture becomes less because of the distance from surface sources and because of low temperatures.

For similar reasons, the area over the Arctic Ocean behaves differently from the other areas of the hemisphere. The winter season at any pressure level is usually too cold to produce as much icing as the summer season; though icing is still a hazard all year.

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[17] Edward D. Heath and Luther M. Cantrell, *Aircraft Icing Climatology for the Northern Hemisphere*, Air Weather Service, USAF Technical Report 220, 1972, p. 2.

[18] *Ibid.*

[19] *Ibid.*, p. 14.

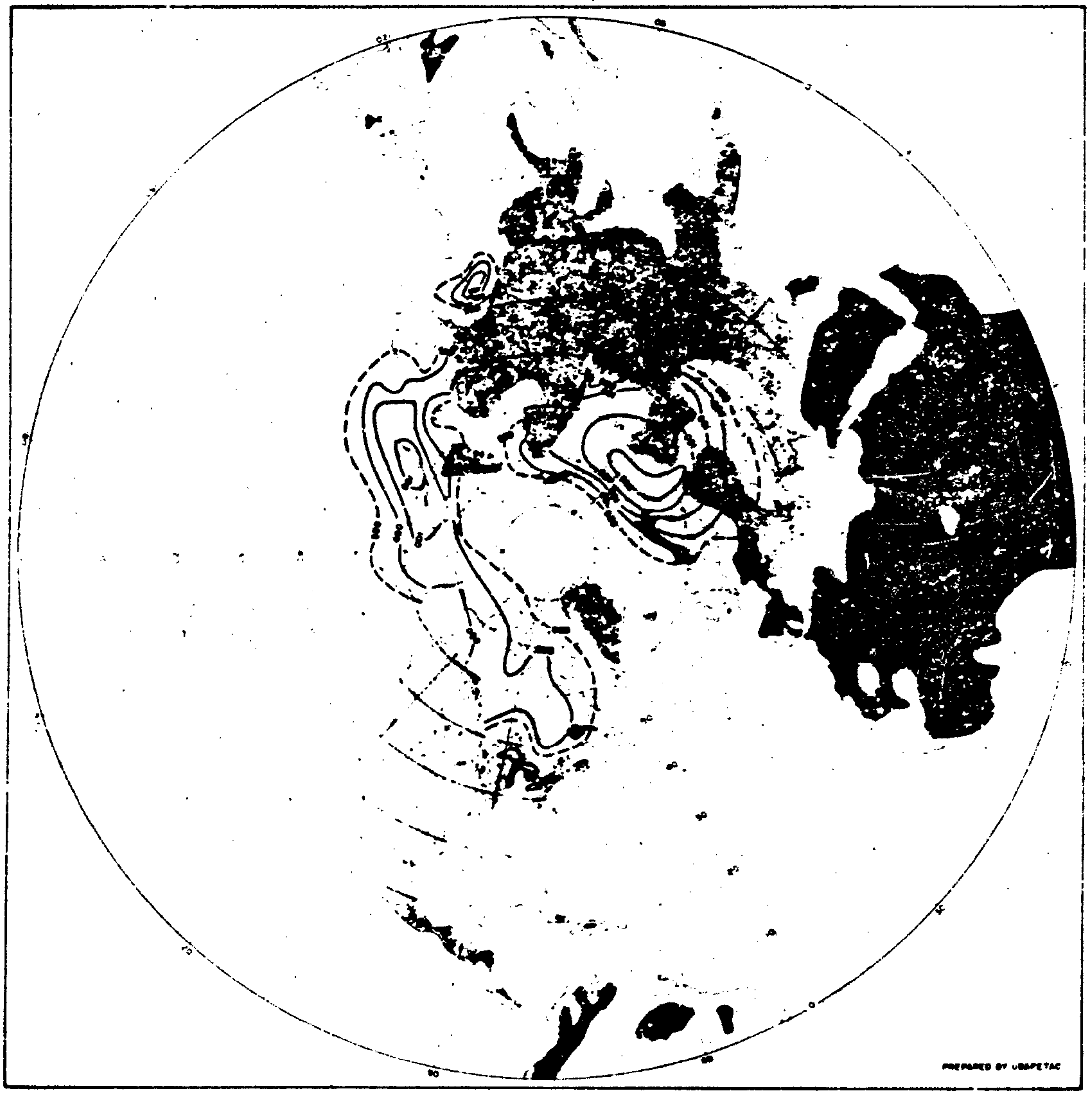

Fig. 20. Probability of encountering icing conditions—1000 mb January—Northern Hemisphere. Shaded areas indicate land surfaces higher than the pressure surface. Source: E. D. Heath et al., *op. cit.*

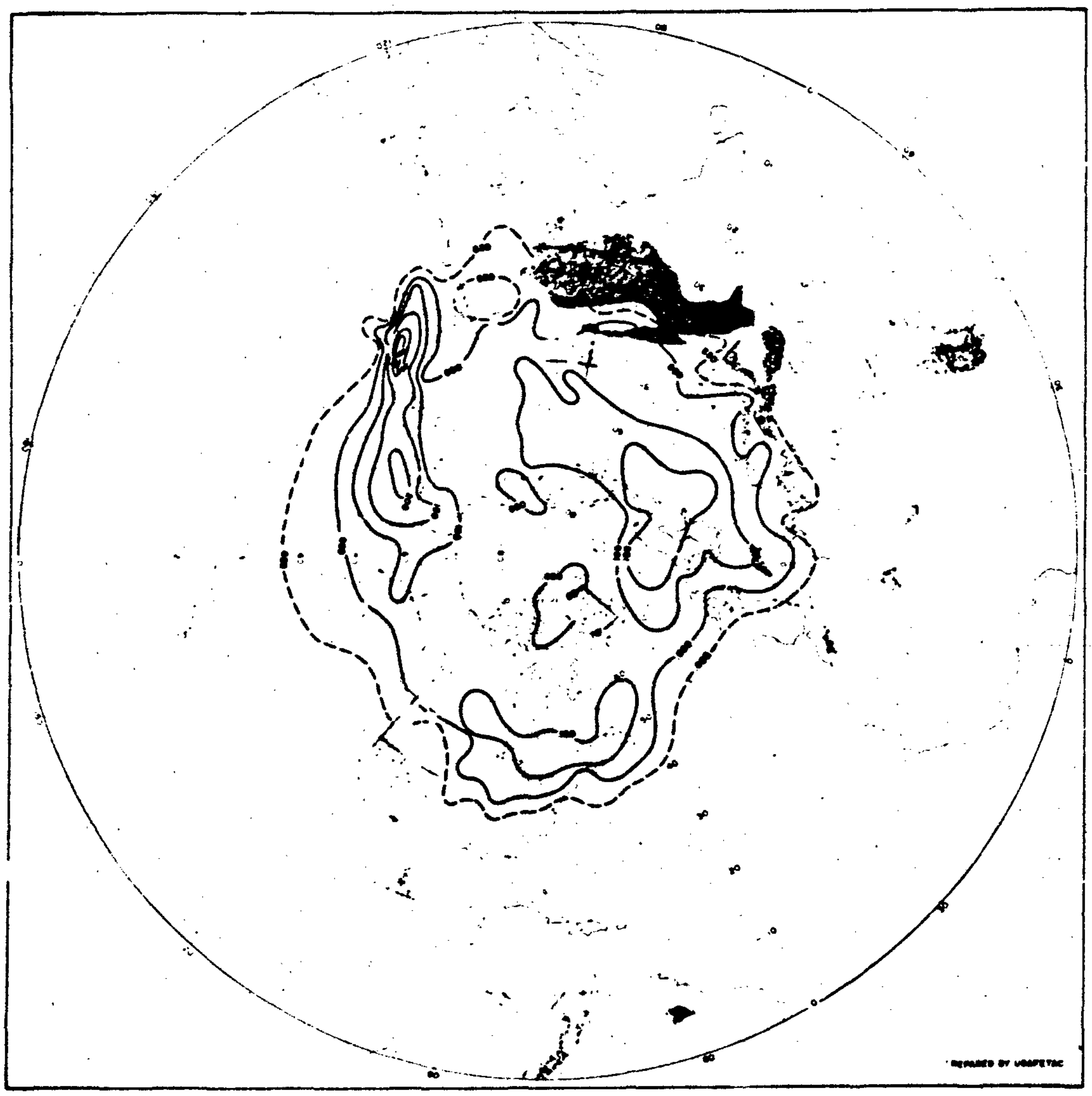

Fig. 21. Probability of encountering icing conditions—850 mb January—Northern Hemisphere. Source: E. D. Heath et al., *op. cit.*

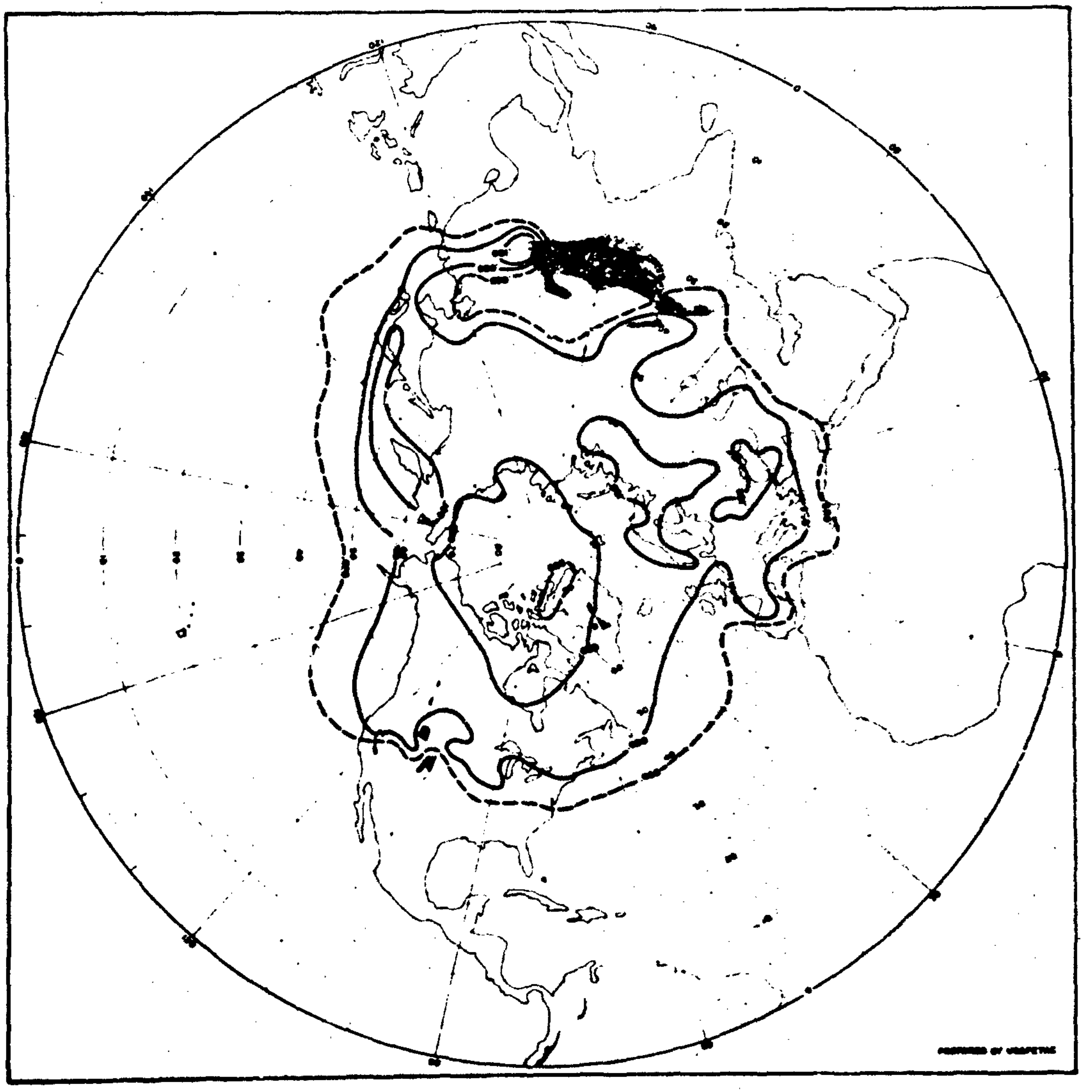

Fig. 22. Probability of encountering icing conditions–700 mb January–Northern Hemisphere.
Source: E. D. Heath et al., *op. cit.*

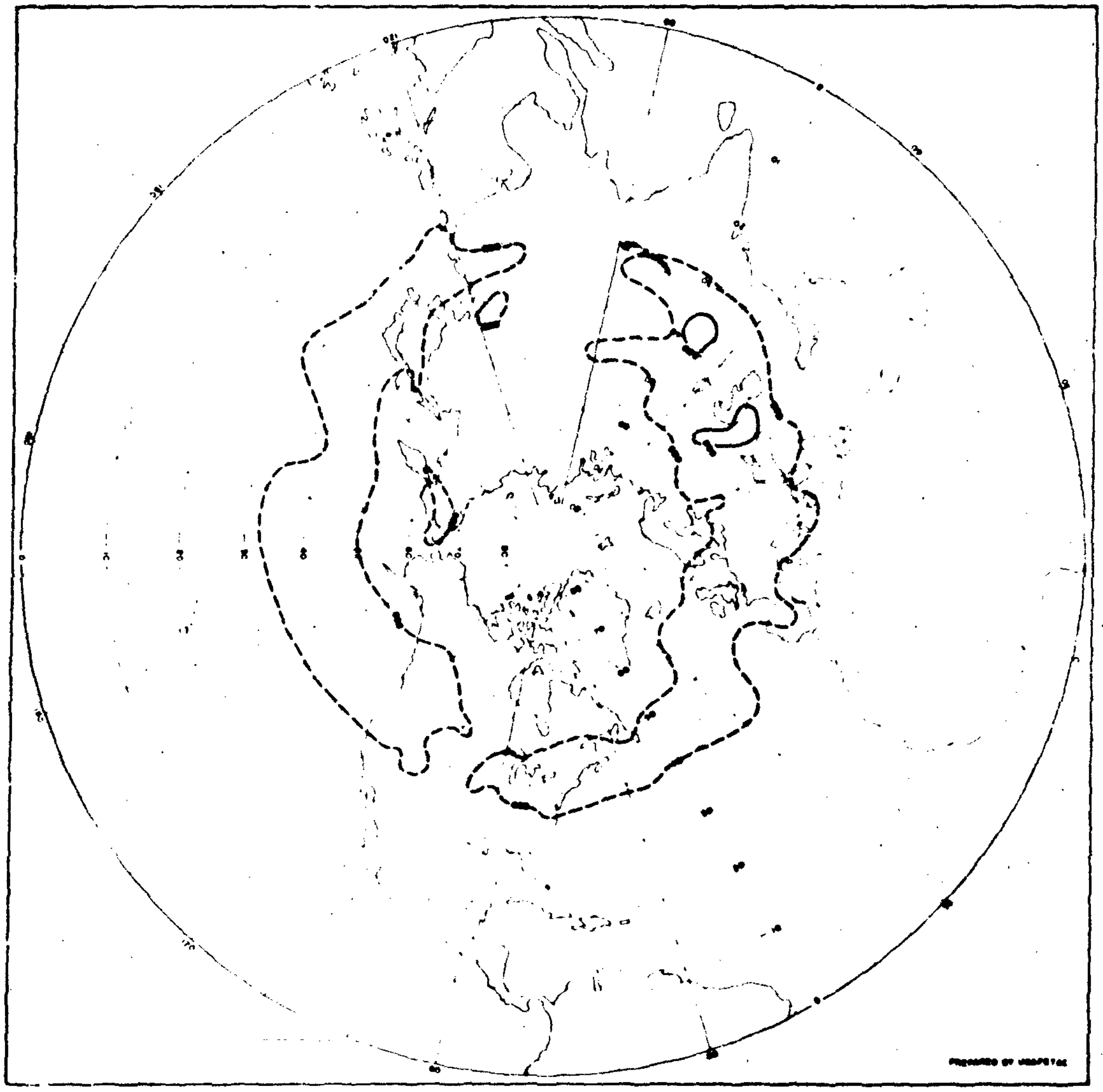

Fig. 23. Probability of encountering icing conditions - 500 mb January - Northern Hemisphere.
Source: E. D. Heath et al., *op. cit.*

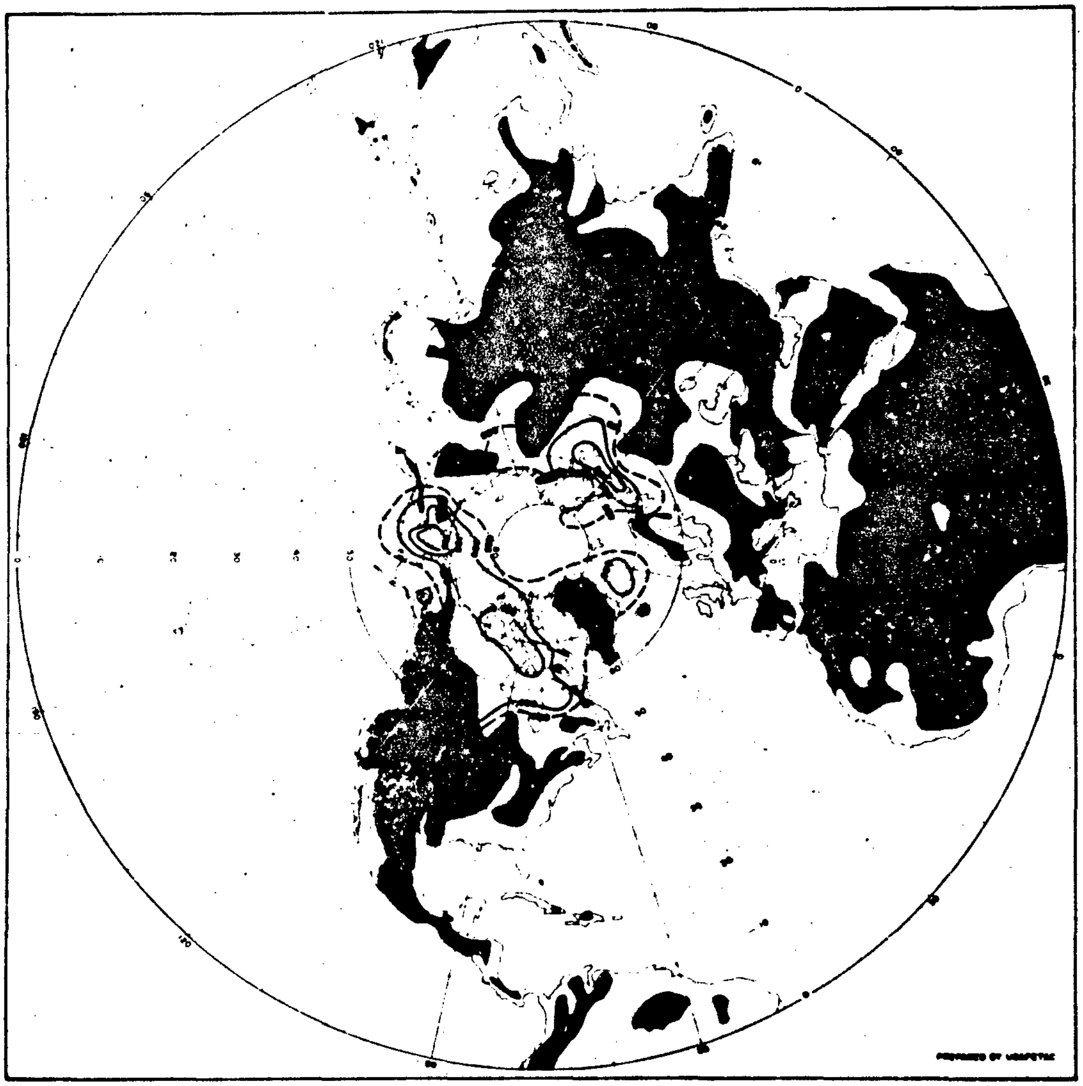

Fig. 24. Probability of encountering icing conditions 1000 mb April Northern Hemisphere.
Source: E. D. Heath et al., *op. cit.*

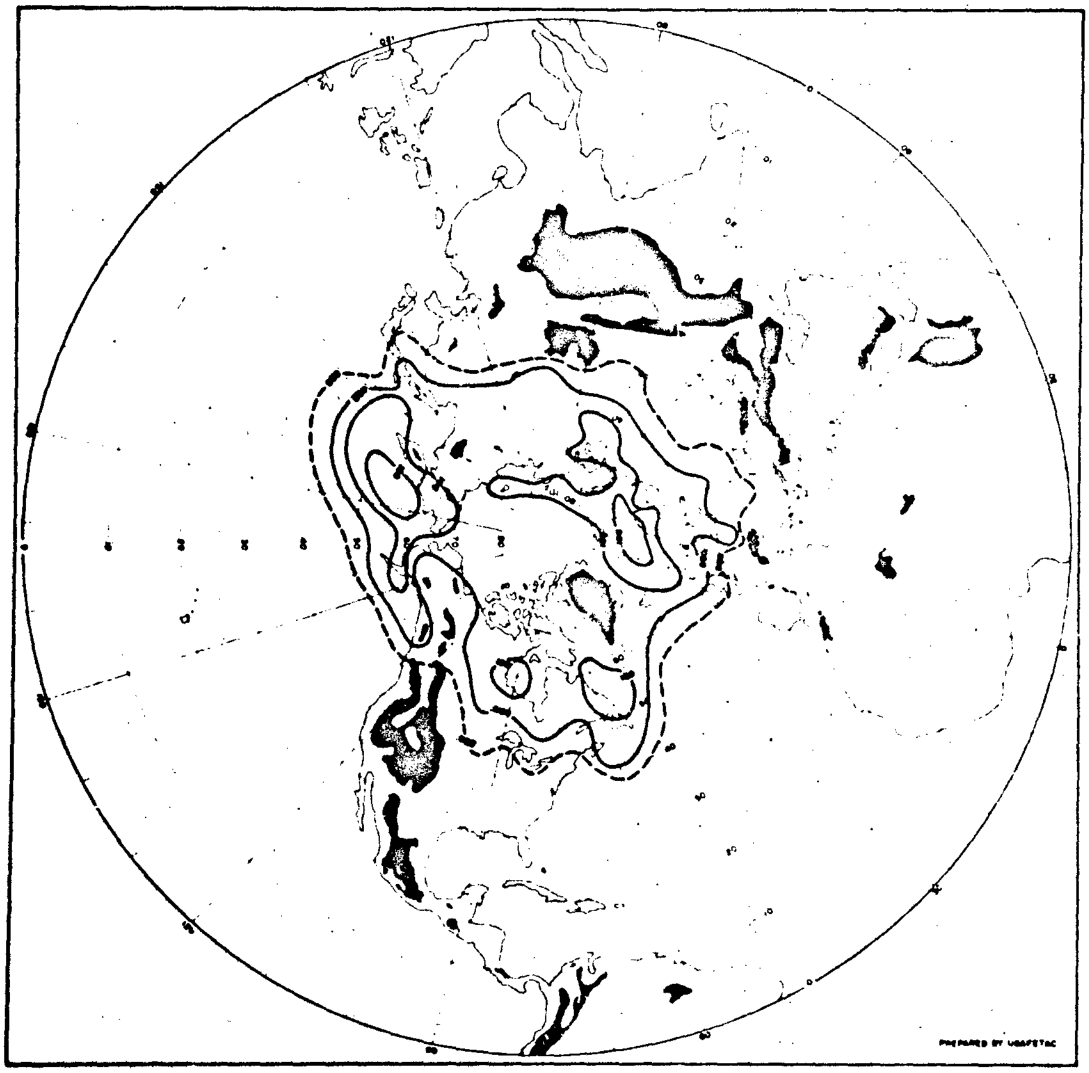

**Fig. 25. Probability of encountering icing conditions—850 mb April—Northern Hemisphere.
Source: E. D. Heath et al., *op. cit.***

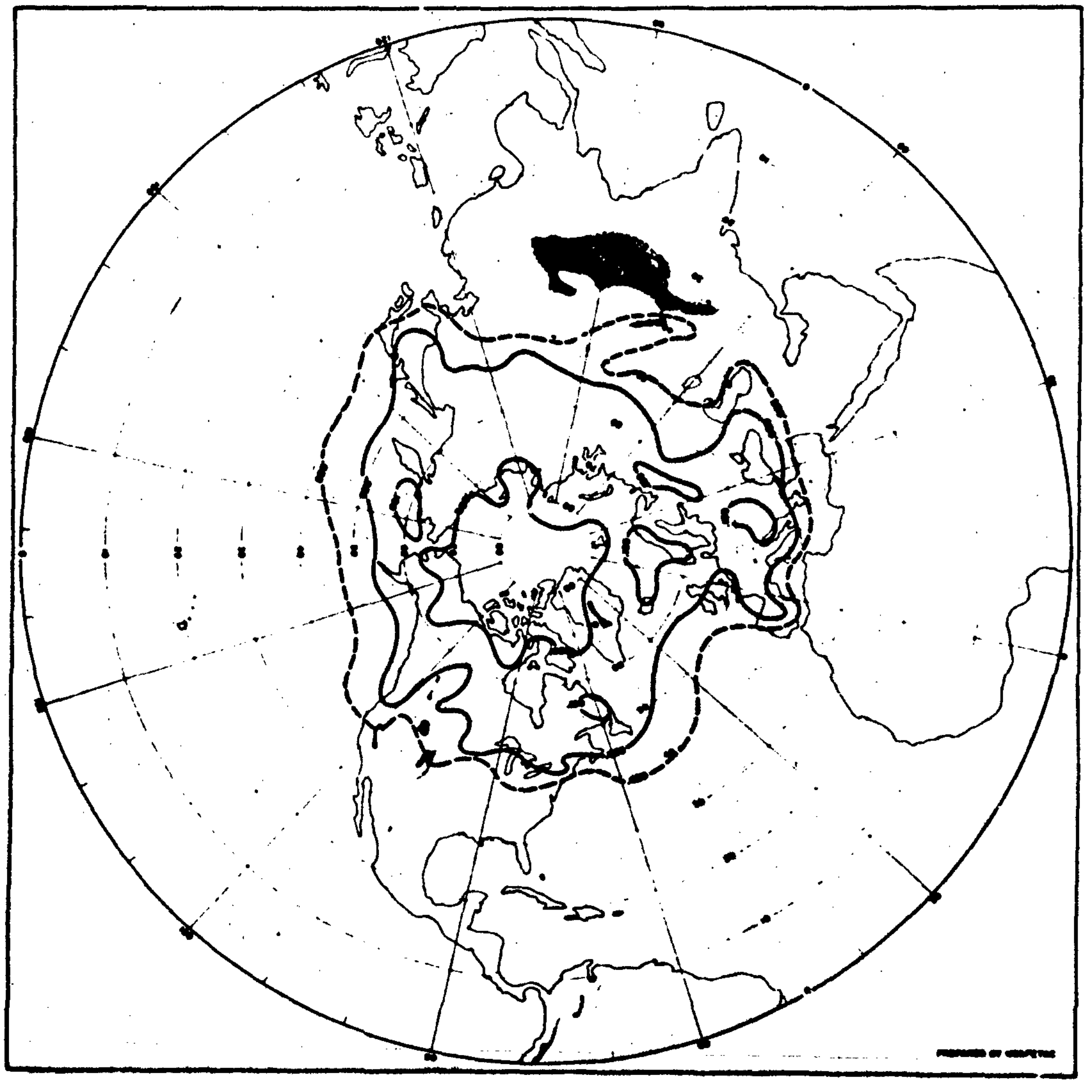

Fig. 26. Probability of encountering icing conditions—700 mb April—Northern Hemisphere.
Source: E. D. Heath et al., *op. cit.*

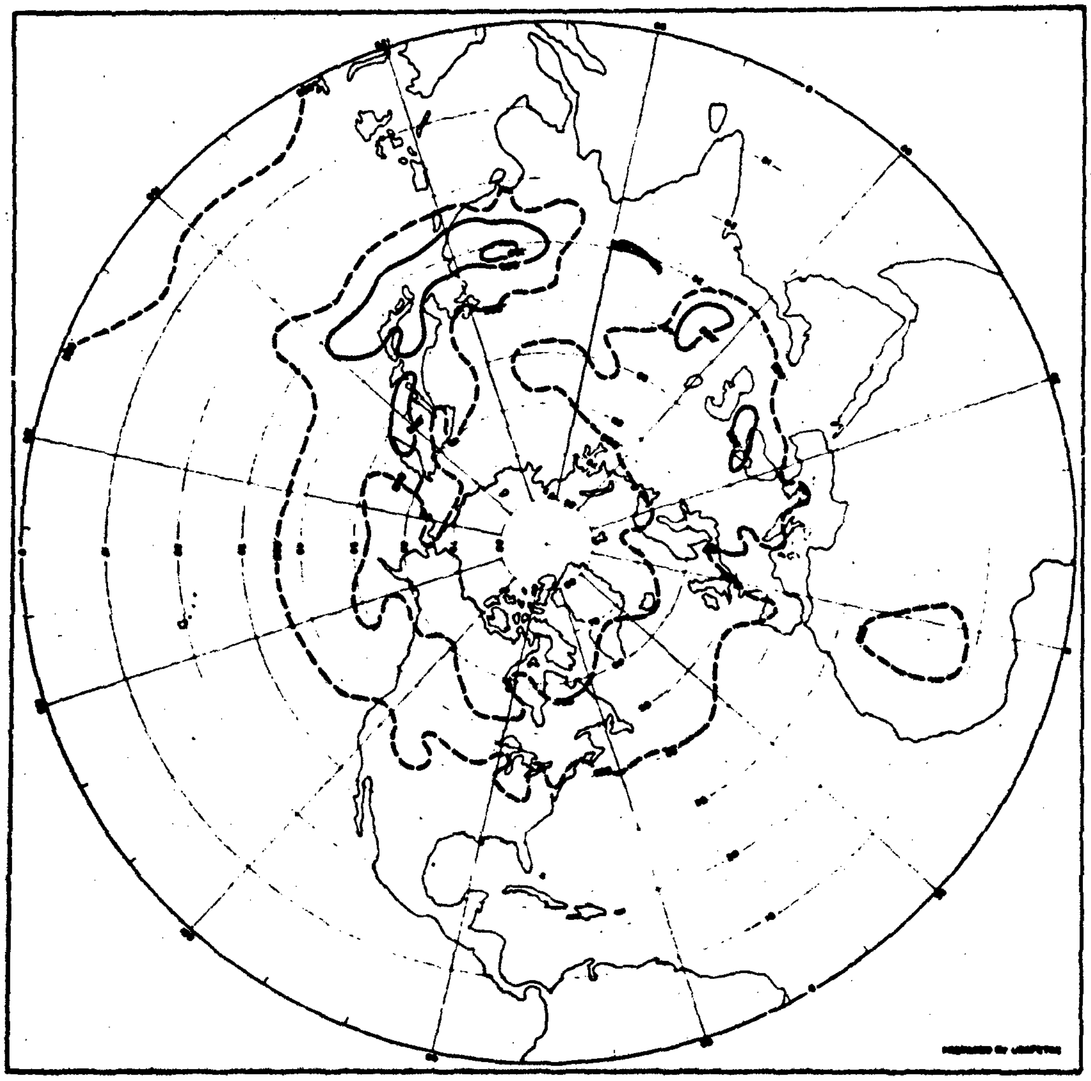

Fig. 27. Probability of encountering icing conditions—500 mb April—Northern Hemisphere.
Source: E. D. Heath, et al., *op. cit.*

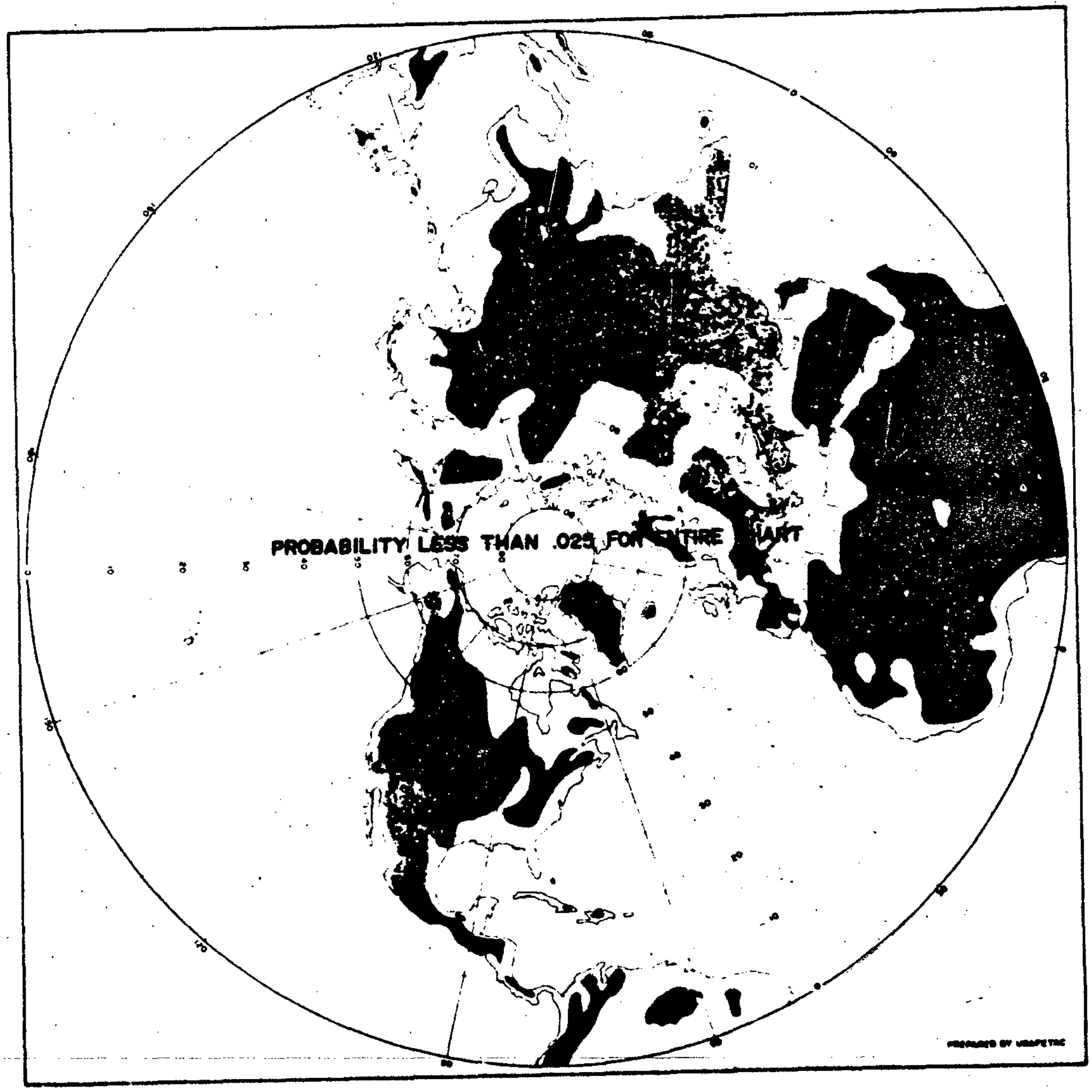

Fig. 28. Probability of encountering icing conditions–1000 mb July–Northern Hemisphere.
Source: E. D. Heath et al., *op. cit.*

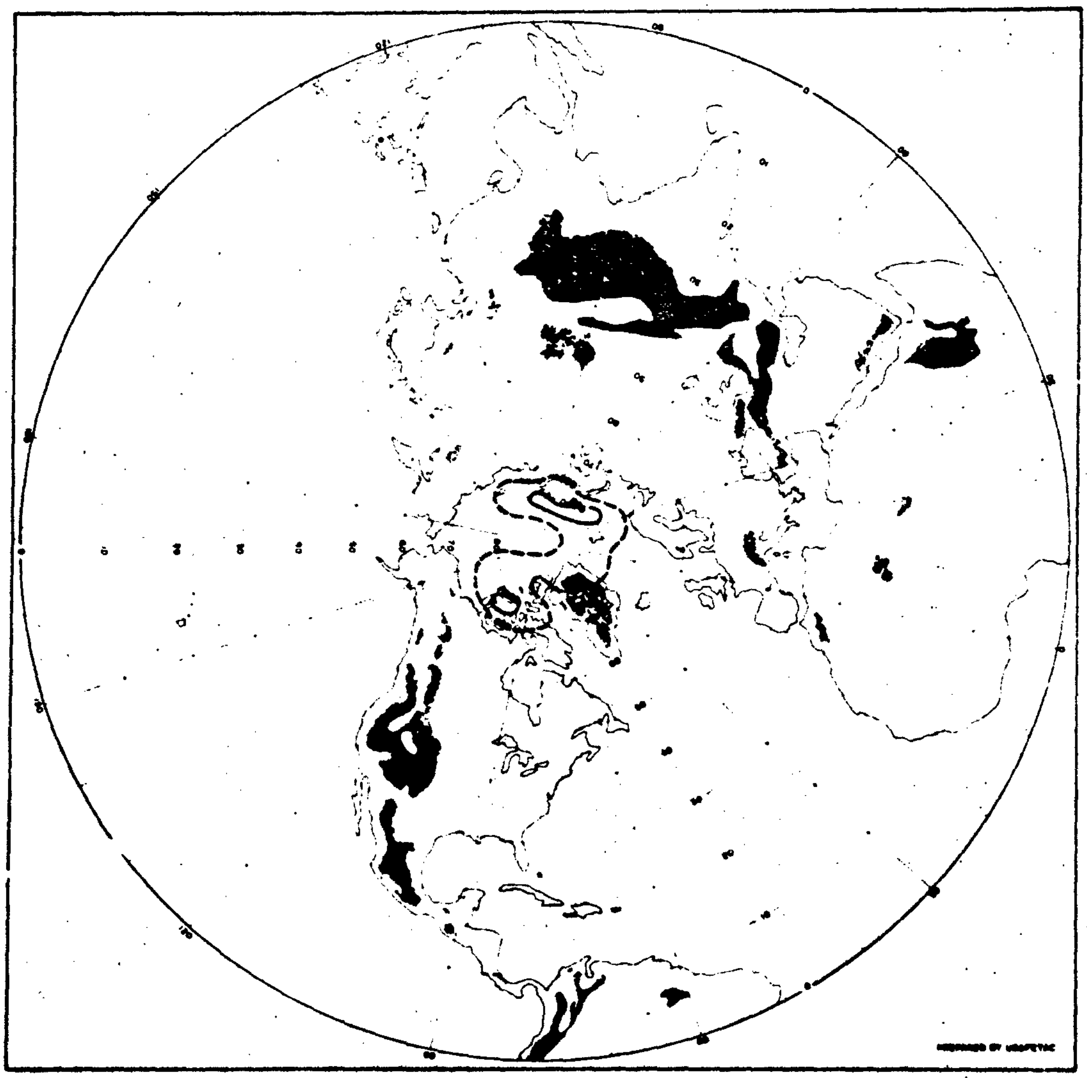

Fig. 29. Probability of encountering icing conditions—850 mb July—Northern Hemisphere.
Source: E. D. Heath et al., *op. cit.*

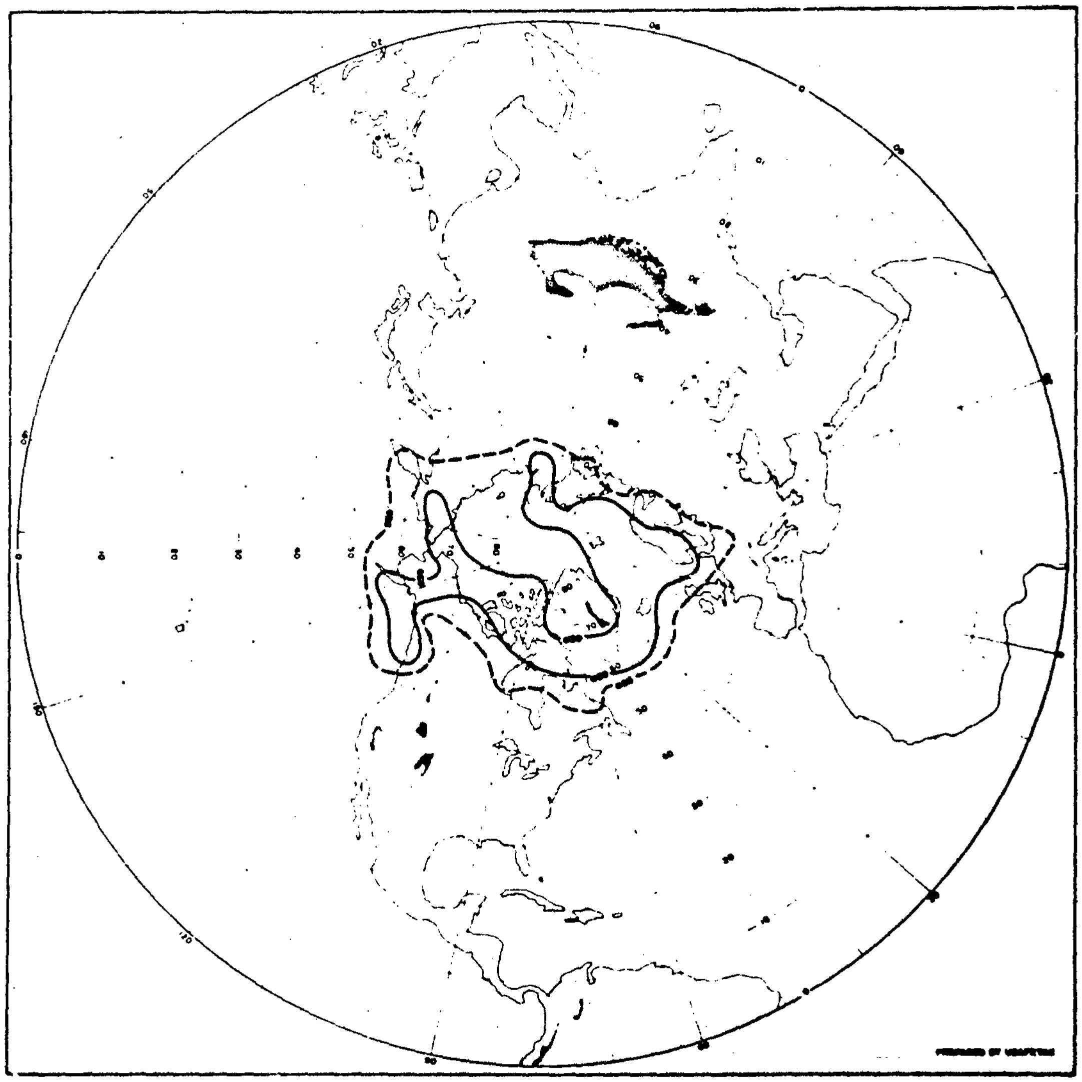

Fig. 30. Probability of encountering icing conditions—700 mb July—Northern Hemisphere.
Source: E. D. Heath et al., *op. cit.*

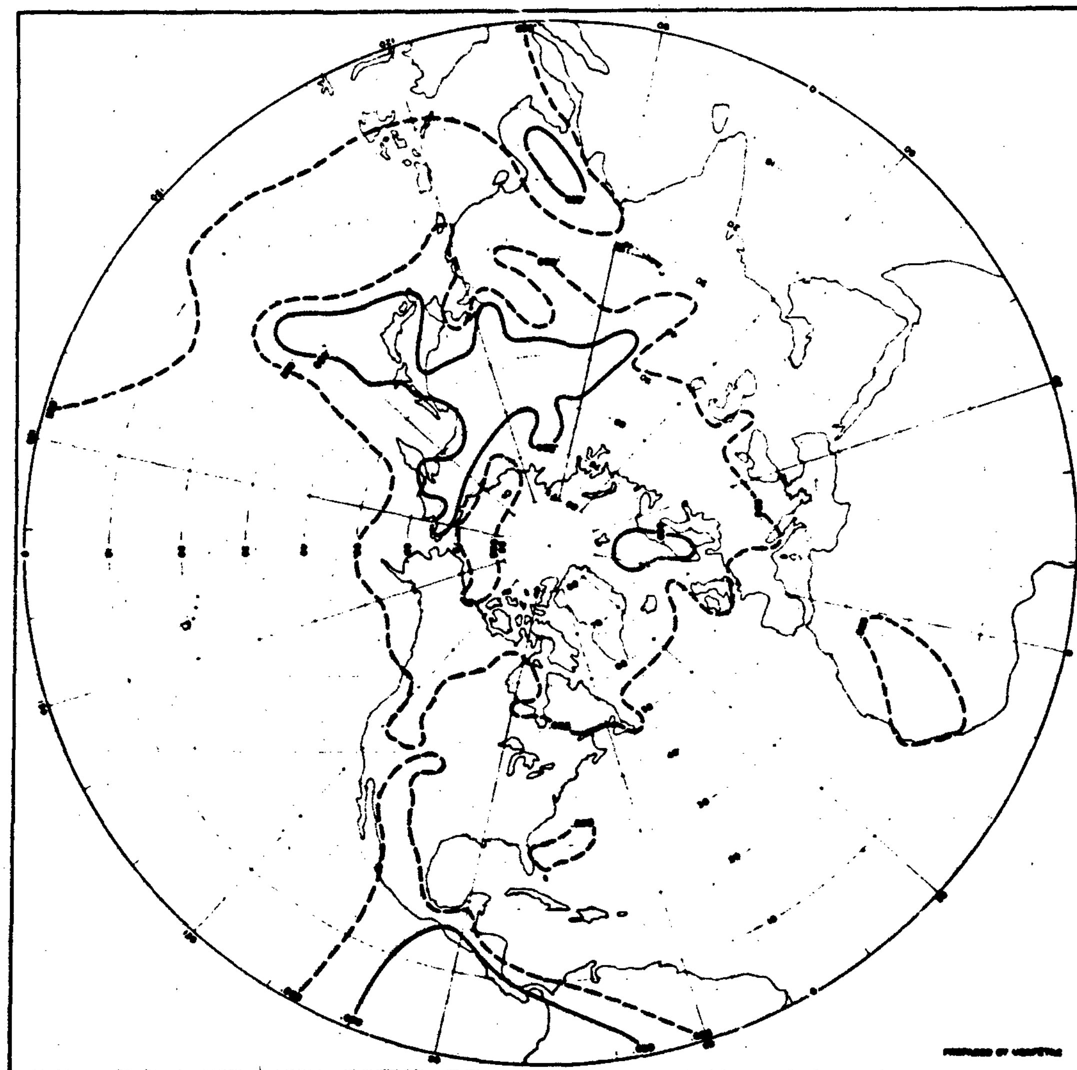

Fig. 31. Probability of encountering icing conditions–500 mb July–Northern Hemisphere.
Source: E.D. Heath et al., *op. cit.*

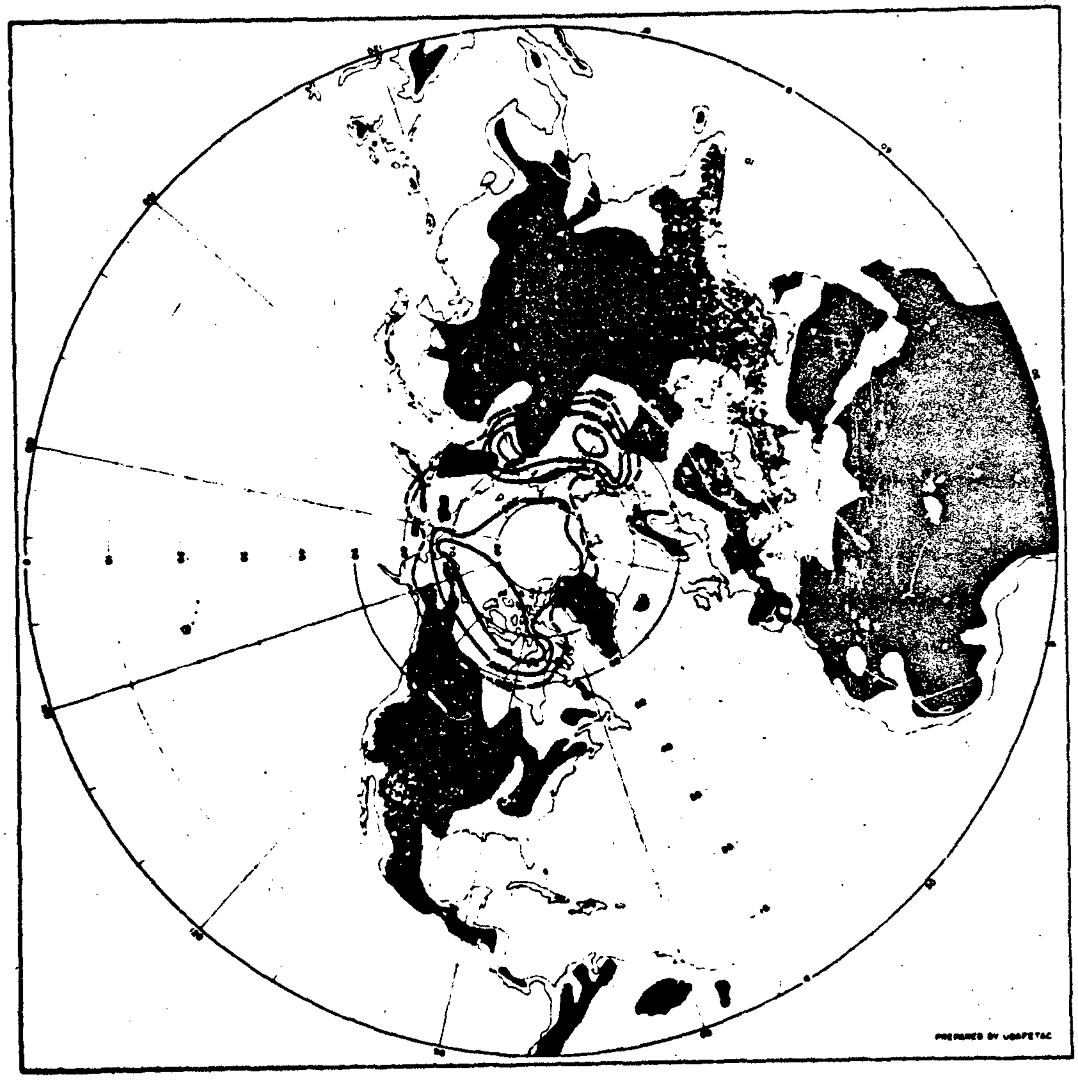

Fig. 32. Probability of encountering icing conditions—1000 mb October—Northern Hemisphere.
Source: E. D. Heath et al., *op. cit.*

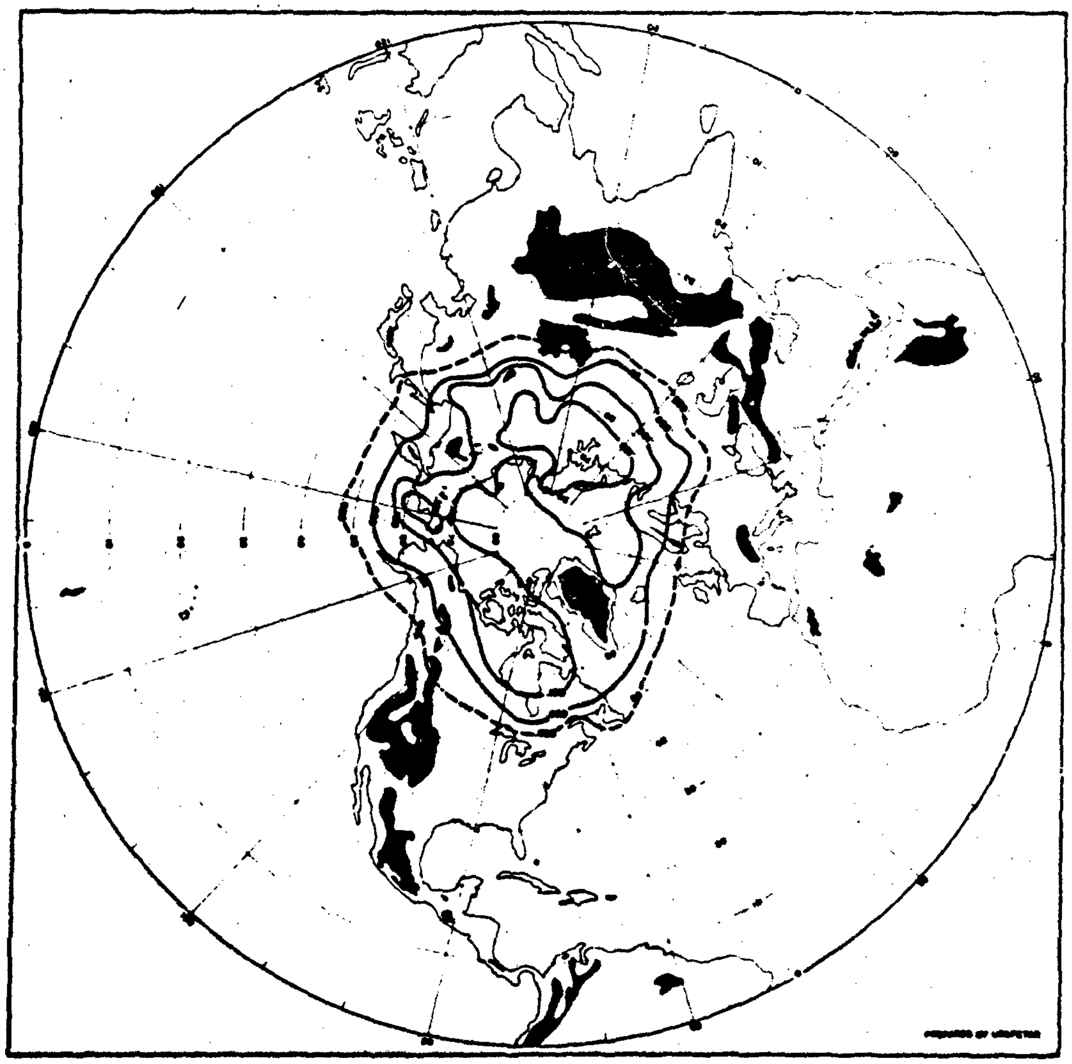

Fig. 33. Probability of encountering icing conditions—850 mb October—Northern Hemisphere.
Source: E. D. Heath et al., *op. cit.*

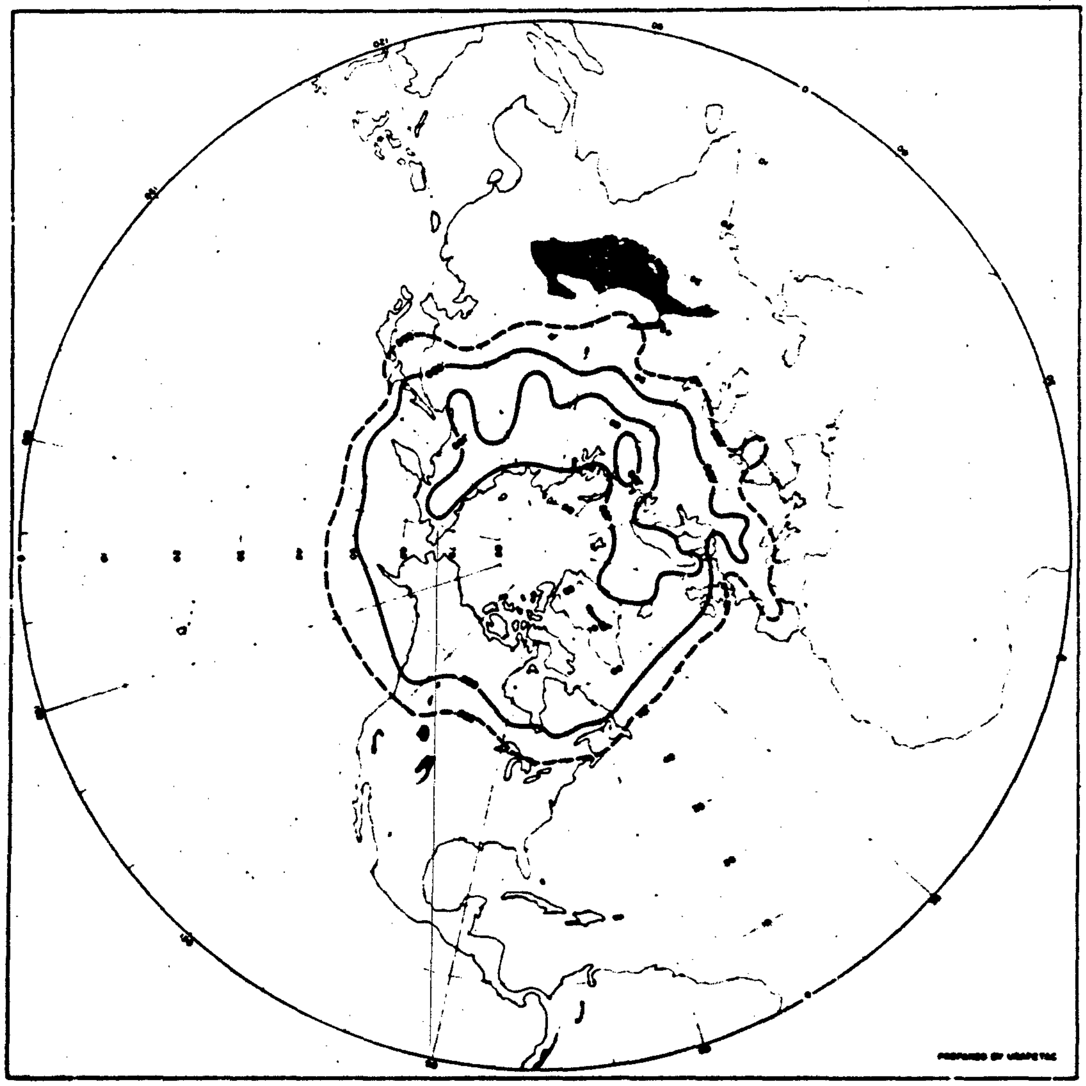

Fig. 34. Probability of encountering icing conditions–700 mb October–Northern Hemisphere.
Source: E. D. Heath et al., *op. cit.*

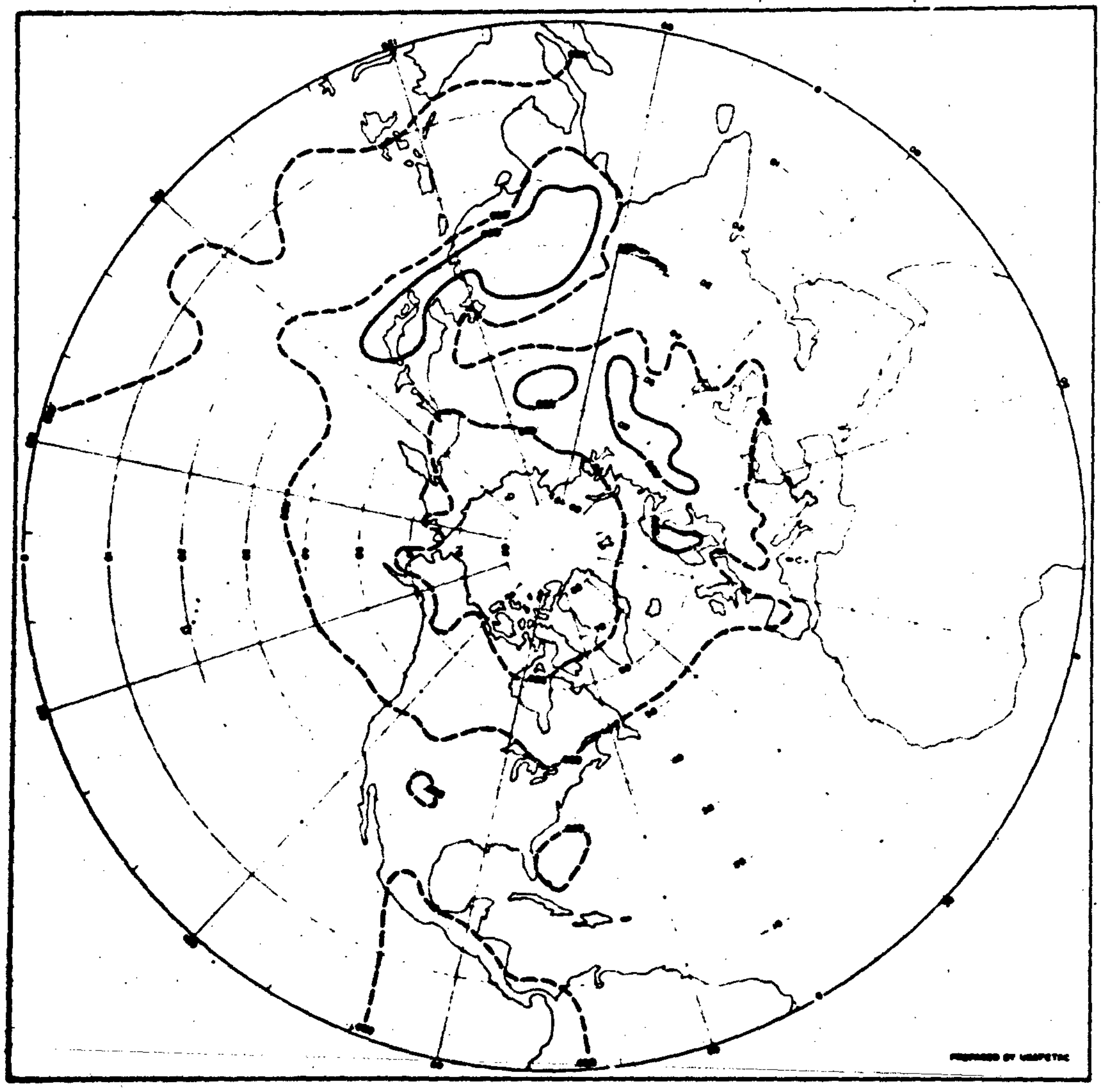

Fig. 35. Probability of encountering icing conditions–500 mb October–Northern Hemisphere.
Source: E. D. Heath et al., *op. cit.*

Mean Heights of Selected Pressure Surfaces at Sample Locations
(ft above MSL)

	1000 mb						700 mb				
	> 75° N Mould Bay NWT	60° N Anchorage, AK	45° N Glasgow, MT	30° N Eglin AFB, FL	<20° N Balboa CZ		> 75° N Mould Bay NWT	60° N Anchorage, AK	45° N Glasgow, MT	30° N Eglin AFB, FL	< 20° N Balboa CZ
Jan	469	240	591	568	305	Jan	8973	9268	9646	10,180	10,299
Feb	417	180	554	515	305	Feb	8861	9206	9596	10,154	10,293
Mar	548	210	482	479	302	Mar	9081	9255	9695	10,161	10,306
Apr	535	213	423	469	295	Apr	9278	9373	9823	10,253	10,319
May	541	299	335	456	285	May	9488	9619	10,003	10,341	10,322
Jun	456	338	272	446	292	Jun	9675	9829	10,092	10,420	10,322
Jul	328	394	315	492	285	Jul	9678	9961	10,289	10,499	10,319
Aug	348	325	289	456	289	Aug	9652	9885	10,240	10,479	10,316
Sep	390	226	358	443	285	Sep	9465	9652	10,102	10,413	10,309
Oct	325	62	413	482	285	Oct	9134	9301	9961	10,322	10,296
Nov	397	72	505	548	282	Nov	9006	9193	9744	10,272	10,286
Dec	371	62	535	577	285	Dec	8901	9072	9734	10,220	10,289
Ann	427	217	427	495	292	Ann	9266	9465	9908	10,312	10,306
	850 mb						500 mb				
Jan	4337	4393	4715	4987	4936	Jan	16,735	17,346	17,841	18,819	19,208
Feb	4252	4341	4675	4957	4930	Feb	16,548	17,257	17,766	18,783	19,201
Mar	4452	4393	4721	4948	4933	Mar	16,837	17,297	17,913	18,809	19,224
Apr	4521	4465	4780	4993	4940	Apr	17,182	17,474	18,143	18,957	19,240
May	4639	4629	4823	5039	4936	May	17,559	17,861	18,524	19,111	19,240
Jun	4692	4741	4833	5075	4936	Jun	17,949	18,238	18,740	19,262	19,234
Jul	4636	4829	4918	5141	4933	Jul	18,048	18,461	19,022	19,364	19,221
Aug	4626	4760	4908	5112	4933	Aug	17,995	18,383	18,973	19,364	19,214
Sep	4560	4600	4875	5069	4930	Sep	17,608	18,015	18,717	19,275	19,201
Oct	4363	4347	4816	5033	4923	Oct	17,077	17,487	18,471	19,104	19,195
Nov	4327	4281	4751	5026	4917	Nov	16,808	17,306	18,035	18,996	19,185
Dec	4255	4213	4738	5016	4923	Dec	16,660	17,103	18,028	18,878	19,201
Ann	4470	4495	4797	5033	4930	Ann	17,251	17,680	18,340	19,062	19,214

Source: E. D. Heath and L. M. Cantrell, *op. cit.*, p. 14.

Statements concerning the probability of encountering icing conditions in the Southern Hemisphere can only be conjectural due to the lack of data. The equatorial patterns at the 500 mb level for the Northern Hemisphere (Figs. 22, 26, 31, and 35) suggest that the patterns continue into the Southern Hemisphere to some extent. Figures 12 through 15 indicate that freezing temperatures exist at the upper levels. Sufficient moisture may be available from warm ocean water off the eastern continental coasts to produce icing at the upper levels over some landmass and midlatitude ocean areas.

III. CONCLUSIONS

3. **Conclusions.** Icing in its many forms is the product of the interaction between diverse meteorological and terrestrial variables. Generalizations as to its characteristic geographical distribution, frequency and probability of occurrence, thickness, and duration are difficult. Latitude, altitude, proximity of warm or cold water, area of landmass, surface morphology, and exposure to sun and wind are only some of the variables in determining these characteristics.

Augmenting these inherent difficulties is the fact that raw data specifically concerning icing occurrences have not been accumulated to any great extent for the world. Collection, analysis, and summarization of available data are limited. Currently, the Air Force Cambridge Research Laboratories are conducting a detailed study of the icing phenomenon.

However, it may be concluded that:

a. Icing develops under a specific and narrow range of meteorological conditions requiring the presence of air temperatures and affected surface temperatures slightly above, at, or below 0° C and moisture that is usually supercooled. However, many times when conditions appear optimal, little or no icing will develop.

b. Ice, commonly in the form of glaze, rime, or hoarfrost, may be deposited during well-defined storms or under less dramatic but numerous circumstances where cold temperatures and moist air occur simultaneously.

c. Surface icing is more of a local phenomenon than a general one.

d. Icing is normally associated with the cold months of the year, but it does occur during the warm season under particular circumstances like those found at the poles and higher elevations.

e. Icing seems to be more common in the Northern Hemisphere, where it occurs mostly from the midlatitudes north to the Pole.

f. The probability of encountering icing conditions in some parts of the atmosphere may be higher because temperature generally decreases with elevation and the clouds in the atmosphere provide a more concentrated supply of moisture.

g. Icing can be severe or light in terms of frequency of occurrence, thickness, or duration depending on local factors. In any case, icing may be disabling to V/STOL aircraft.

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